NEGATIVE RESISTANCE CHARACTERISTICS
AND USES OF CRYSTAL DIODES

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Davies Powell Anderson

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NEGATIVE RESISTANCE CHARACTERISTICS

AND USES OF CRYSTAL DIODES

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Date Approved by Chairman Aug. 12, 1948

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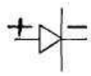
LIST OF SYMBOLS

 - Crystal diode (polarity indicates direction of maximum conduction)

R_b - Bulk resistance of the diode

R_o - Barrier resistance of the diode

C_o - Barrier capacitance of the diode

$\frac{\Delta E}{\Delta I}$ - Negative resistance of the dynamic equivalent circuit of the diode

R_s - Positive resistance of the dynamic equivalent circuit of the diode

CRO - Cathode-Ray Oscilloscope

V - Half-wave rectifier

R_c - Series resistance used in obtaining diode characteristics dynamically

R' - Potentiometer resistance

R_1 - Resistance above potentiometer arm (see Figure 18)

R_2 - $R' - R_1$

E_b - Supply voltage

L - Resonant inductance

C - Resonant capacitance

R - Total resistance in sine-wave oscillator

L_s - Blocking inductance

i - Oscillatory current

t - Time measured from zero current

f_n - Natural resonant frequency

f_m - Measured frequency

NEGATIVE RESISTANCE CHARACTERISTICS
AND USES OF CRYSTAL DIODES

INTRODUCTION

Historical Background

Crystal diodes have been used to replace the vacuum tube in many applications of the past. Their light weight, small size, and low power requirements gave them many advantages over the bulky vacuum tube. Their use lapsed, however, until the urgent requirements of radar brought them forward once more. Although new types of crystal diodes have been developed, most of the basic applications are the same. These include detection, rectification, and frequency conversion. One of the modern type units, the 1N34 germanium diode, is shown in Figure 1.

Scope of the Investigation

It is the purpose of this paper to discuss the characteristics of the germanium crystal diode and investigate some of its applications in the negative resistance region. The equivalent circuit for frequencies less than 100 megacycles is described, as well as the various types of negative resistance characteristics of the crystal diode. Furthermore, methods for obtaining the characteristic curve of the diode are described and analyzed.

Applications of the negative resistance characteristic include practical oscillator circuits. To complete the investigation, a mathematical analysis is presented to justify the results for the sine-wave oscillator.

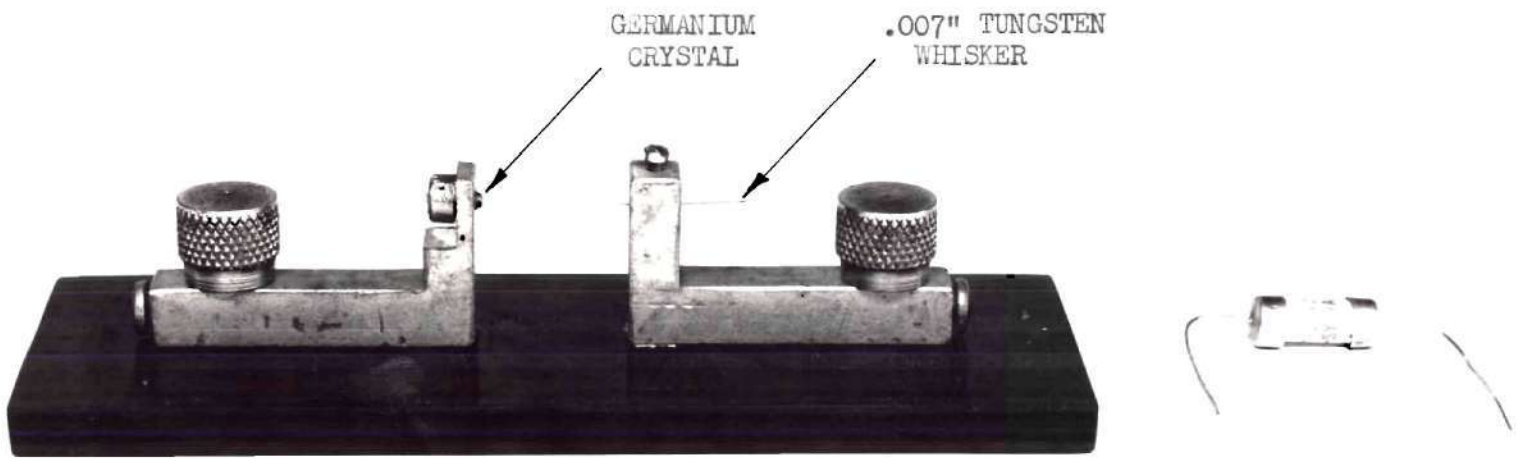


FIG. 1 SPECIAL CRYSTAL DIODE MOUNTING AND COMMERCIAL 1N34 DIODE

CHARACTERISTICS OF CRYSTAL DIODES

Equivalent Electrical Circuit

The equivalent circuit of the crystal diode, as shown in Figure 2, applies for all frequencies up to 100 megacycles. Two factors contribute to its impedance. One is the bulk resistance, R_b, which is constant; the other is the contact or barrier impedance. The barrier impedance consists of a resistance, R_o, and a capacitance, C_o, in parallel, and is not constant. The bulk resistance depends on the resistivity of the basic crystal element, and the contact area. The resistance of the barrier impedance varies with the magnitude and polarity of the applied voltage, and the capacitance is a function of applied voltage, as well as of physical size. The resistance, R_o, is very high in the inverse direction but very small in the forward direction. The terminal capacitance of the commercial 1N34 diode pictured in Figure 1 is 3.0 micromicrofarads.

Mention might be made here that the special crystal mounting was devised to allow a larger size whisker wire to be used than was provided in the 1N34 and to facilitate adjustment of the whisker. This was necessitated by the fact that the small size whisker used in the 1N34 burned out frequently during the progress of this investigation.

Detailed information on the impedance and make-up of crystal diodes may be found in the literature.[1]

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[1]E. C. Cornelius, "Germanium Crystal Detectors," Electronics, Vol. 19, No. 2, pp. 118-123, February, 1946.

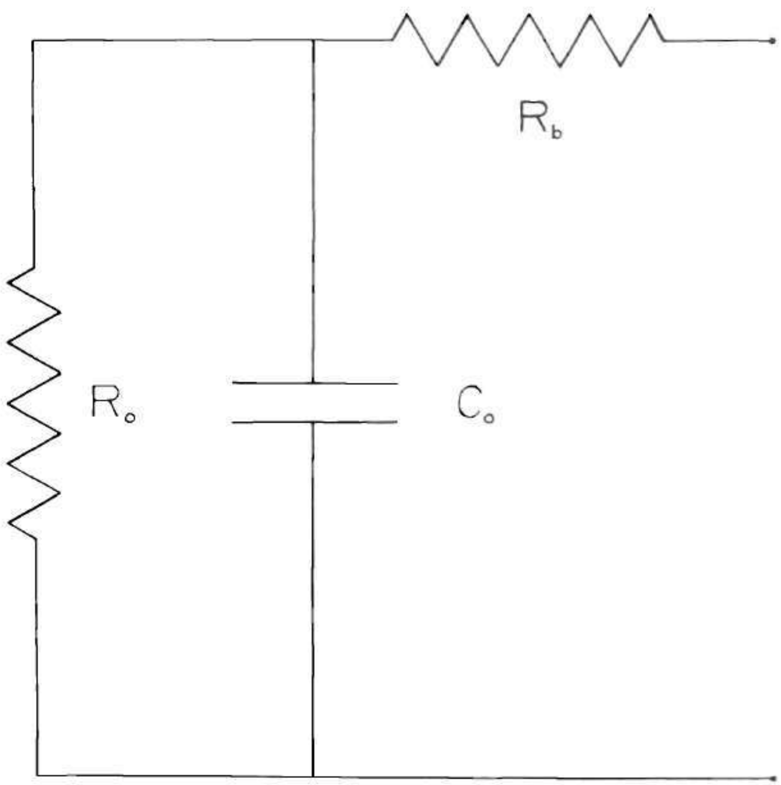

FIGURE 2
STATIC EQUIVALENT CIRCUIT

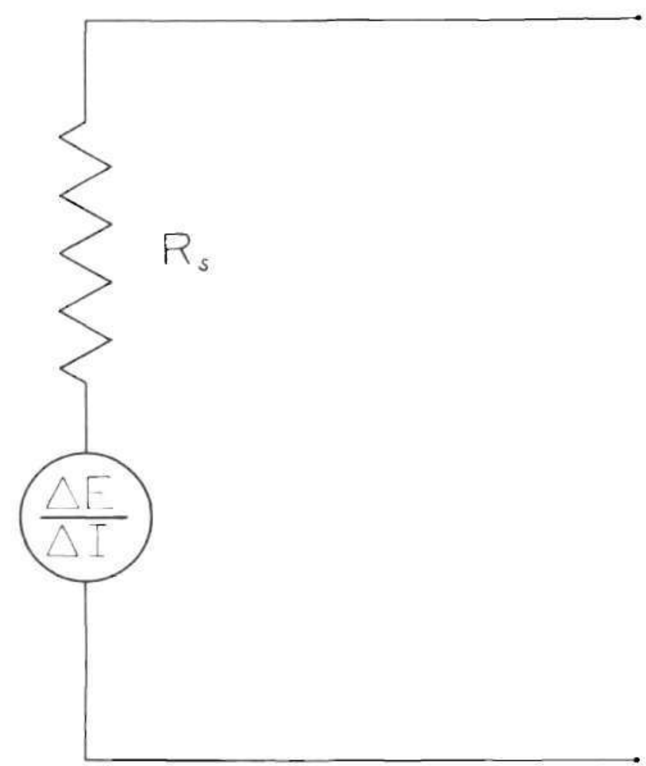

FIGURE 3
DYNAMIC EQUIVALENT CIRCUIT

The Characteristic Curve

The germanium type of crystal diode has been used primarily as a rectifier. Along with the silicon diode, the germanium diode has covered the field of requirements in detectors and rectifiers. There is one property of the crystal diode, however, which has not been employed to any great extent as yet. That is the negative slope of the characteristic curve in certain regions. The region of greatest slope occurs past the breakdown point in each crystal. This breakdown point is usually between 40 and 80 volts negative. A particular diode, of course, could only be an effective rectifier for peak voltages less than the breakdown voltage.

The complete characteristic curve of a germanium diode is pictured in Figure 4. Different crystal diodes will not have identically the same characteristics, but these curves will have the same general shape. These characteristics will have a definite peak in the inverse direction and a more or less gradual slope toward the current axis. The type of negative resistance exhibited by the crystal diode is current-controlled as opposed to voltage-controlled negative resistance in other devices.[2]

Five of the distinct types of characteristics mentioned in the literature are the low negative resistance, the high negative resistance, the double peaked, the side step breakdown, and the oscillation.[3] A common and desirable characteristic for many uses is the high negative resistance type, of which Figure 4 is a good example. The low negative

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[2]E. W. Herold, "Negative Resistance and Devices for Obtaining It," Proceedings of the Institute of Radio Engineers, Vol. 23, No. 10, pp. 1204-5, October, 1935.

[3]E. C. Cornelius, *op. cit.*, p. 121.

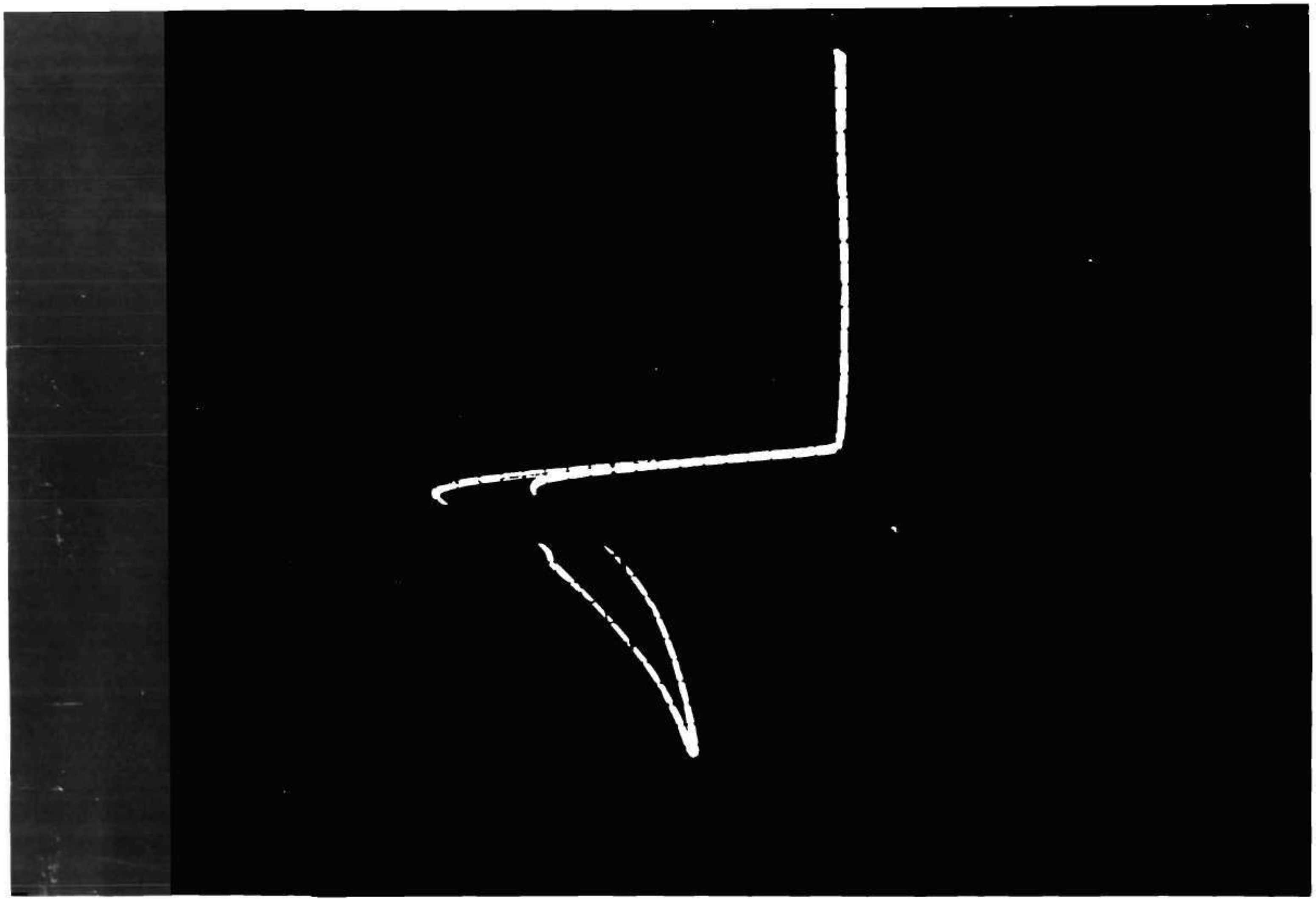

FIG. 4 TYPICAL CRYSTAL DIODE CHARACTERISTIC

resistance characteristic is shown in Figure 5, and the peaked characteristic with oscillations in Figure 6. Other characteristics are shown in Figures 7 through 11.

These various types of curves depend on the kind of crystal, the type and amount of any other element alloyed with it, the whisker material, and the crystal temperature. Since the germanium diode is known to have a high negative resistance, it was chosen for this investigation. The crystal of the 1N34 diode is a germanium-tin semi-conductor. The tin is a small percentage of the alloy but gives the crystal structure the desired lattice-imperfection characteristics. The next most important element of the diode is the whisker material. Its many physical properties, including the contact difference of potential, are important. Considering all factors, tungsten was chosen in the manufacture of the 1N34[4] and was used in the special mounting.

The contact area between the germanium and tungsten is very critical. The burn-out point of the crystal depends on that area.[5] Furthermore, the resistance, R_b, of the equivalent circuit, is inversely proportional to the area.

The temperature is important because it governs the potential at which breakdown occurs. Since most of the heat generated at the contact passes through the crystal, this condition is aggravated. Breakdown causes the characteristic to become flat, or have a low negative resist-

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[4]Ibid., pp. 118-119.

[5]A. W. Lawson, M. N. Lewis, P. H. Miller, and W. E. Stephens, "Comparison of Wedge and Cone Contacts on Fox Silicon," Division 14, NDRC, Report 14-197, October 22, 1943.

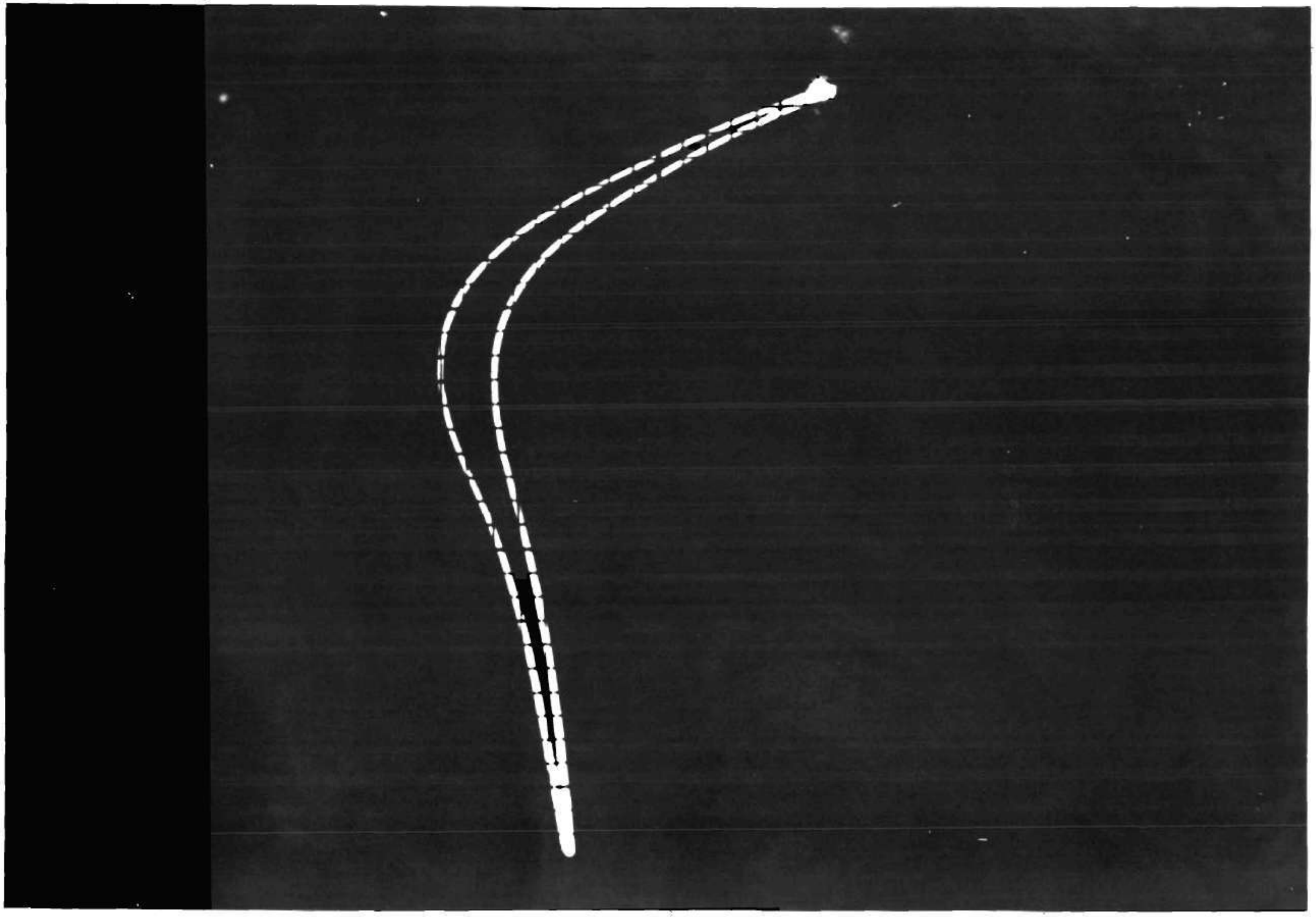

FIG. 5 LOW NEGATIVE RESISTANCE CHARACTERISTIC

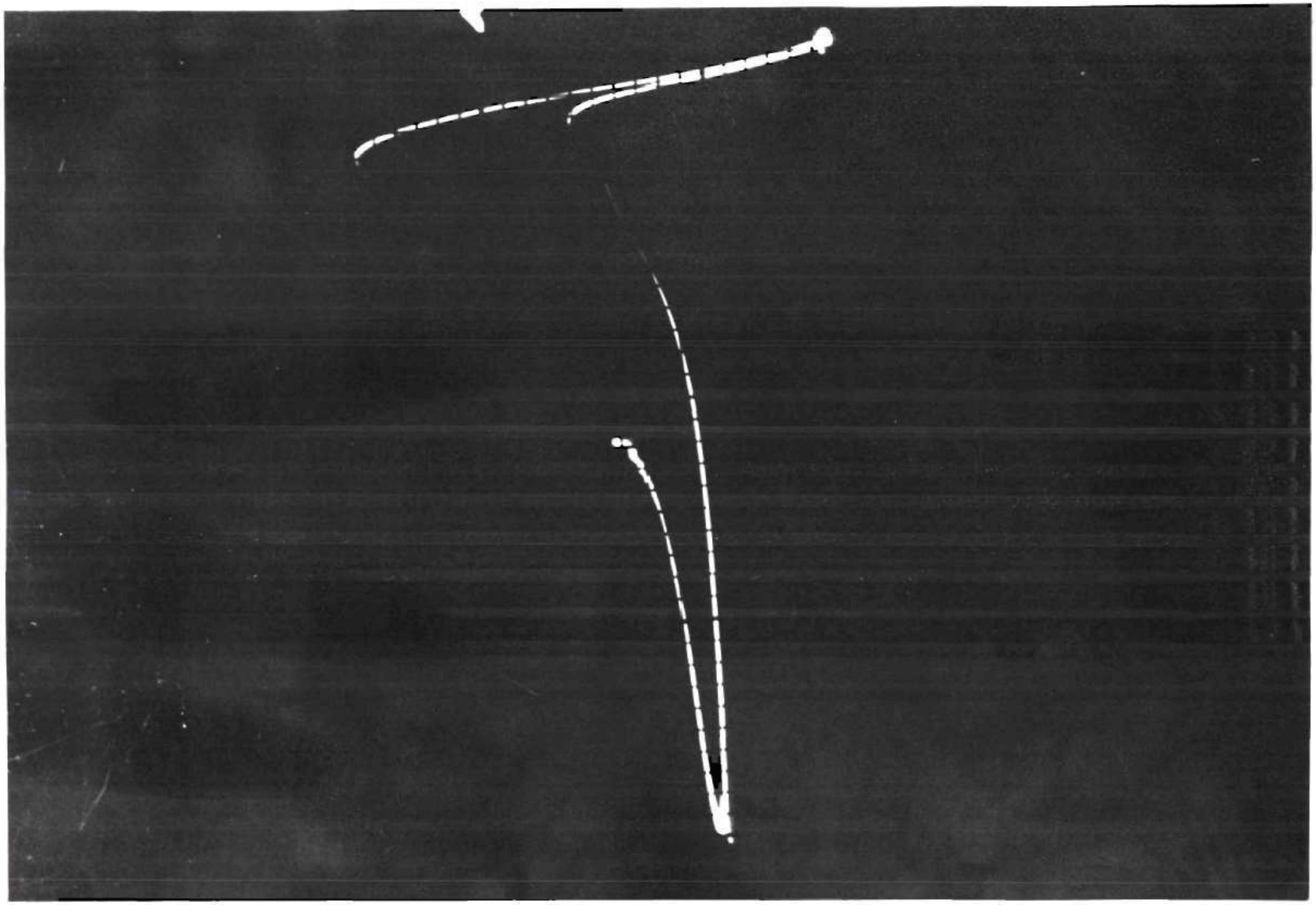

FIG. 6 HIGH NEGATIVE RESISTANCE WITH OSCILLATORY PEAKS

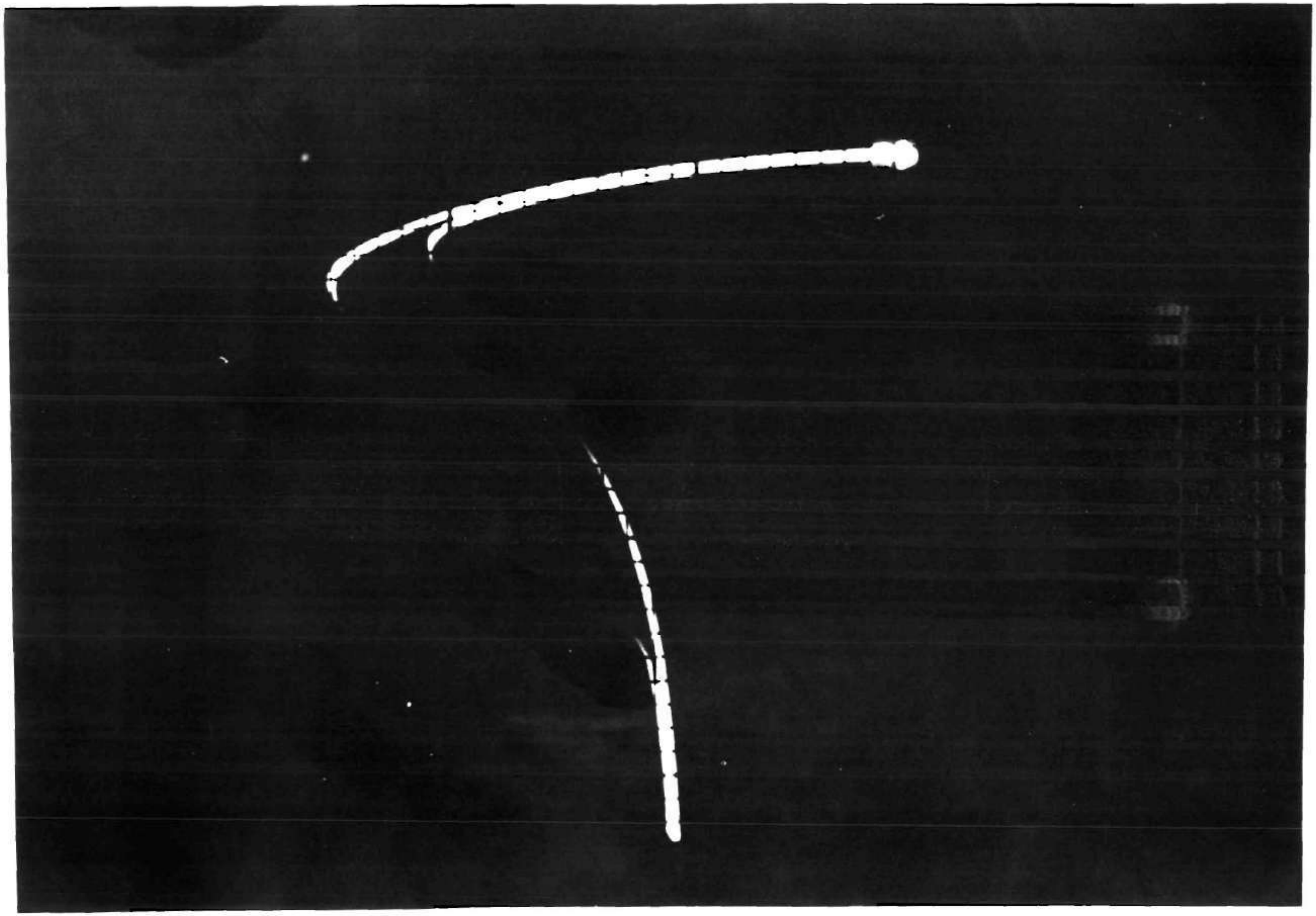

FIG. 7 UNUSUAL CRYSTAL DIODE CHARACTERISTIC

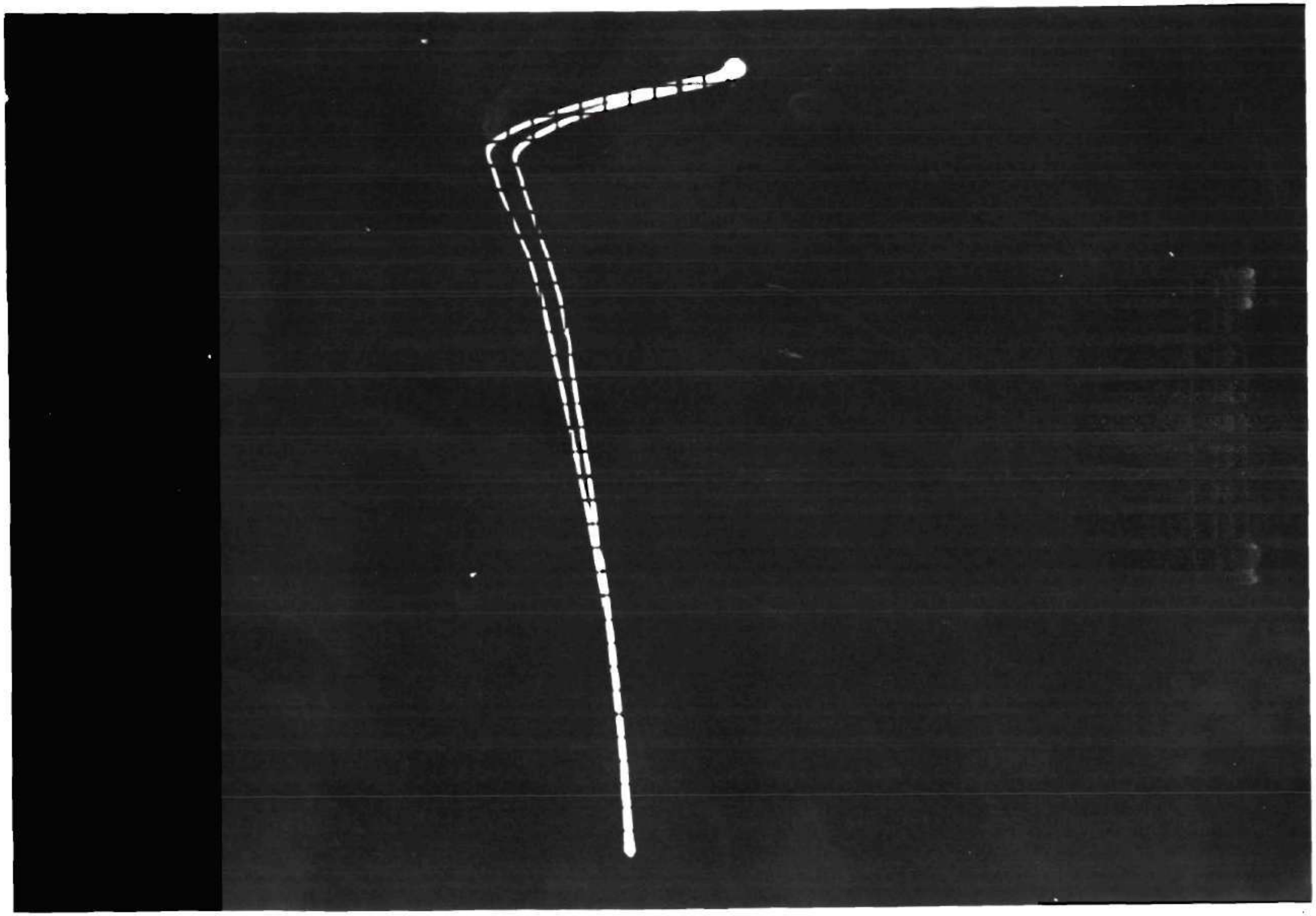

FIG. 8 ANGULAR BREAK OF CRYSTAL DIODE CHARACTERISTIC

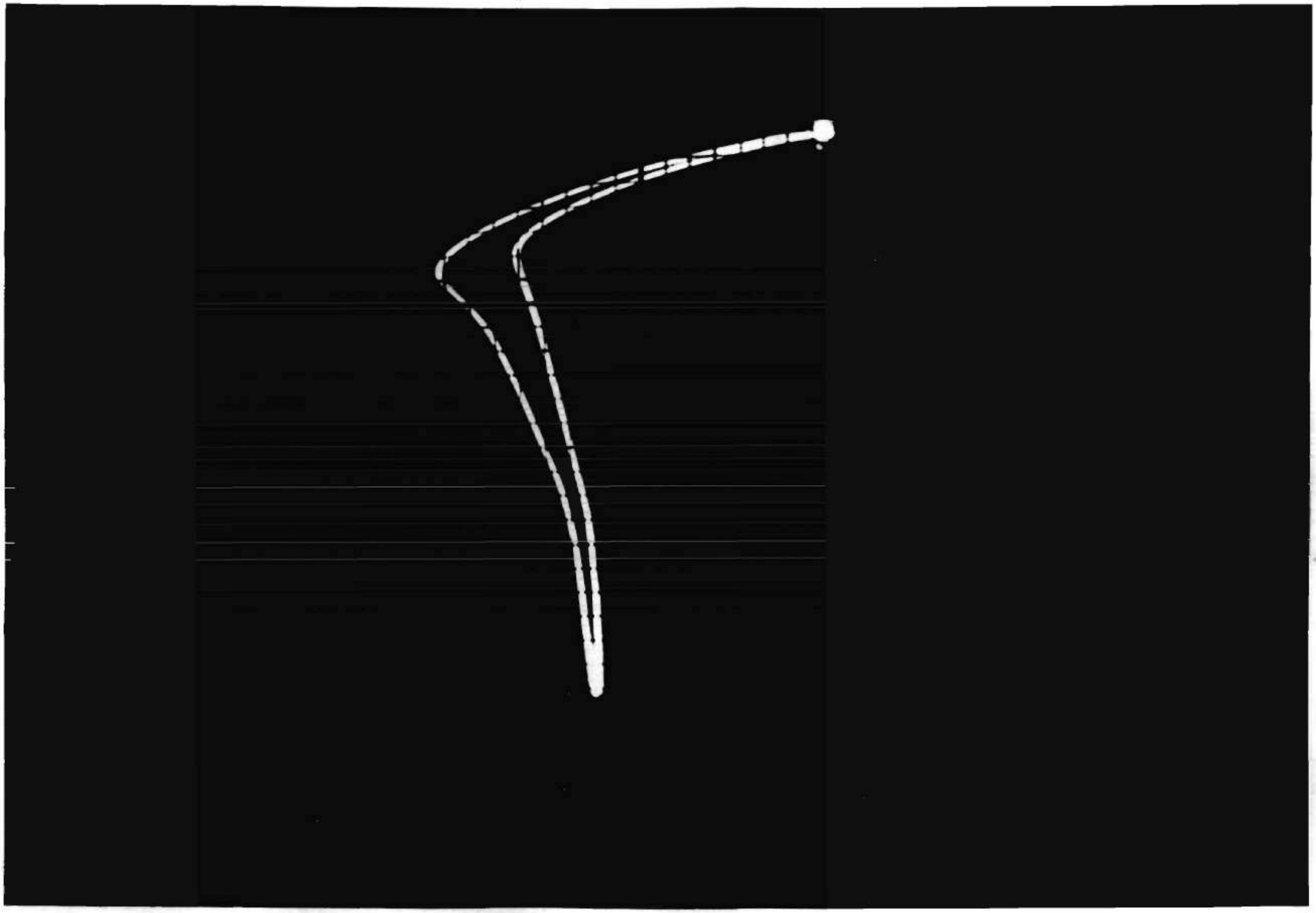

FIG. 9 CHARACTERISTIC OF COMMERCIAL 1N34 DIODE

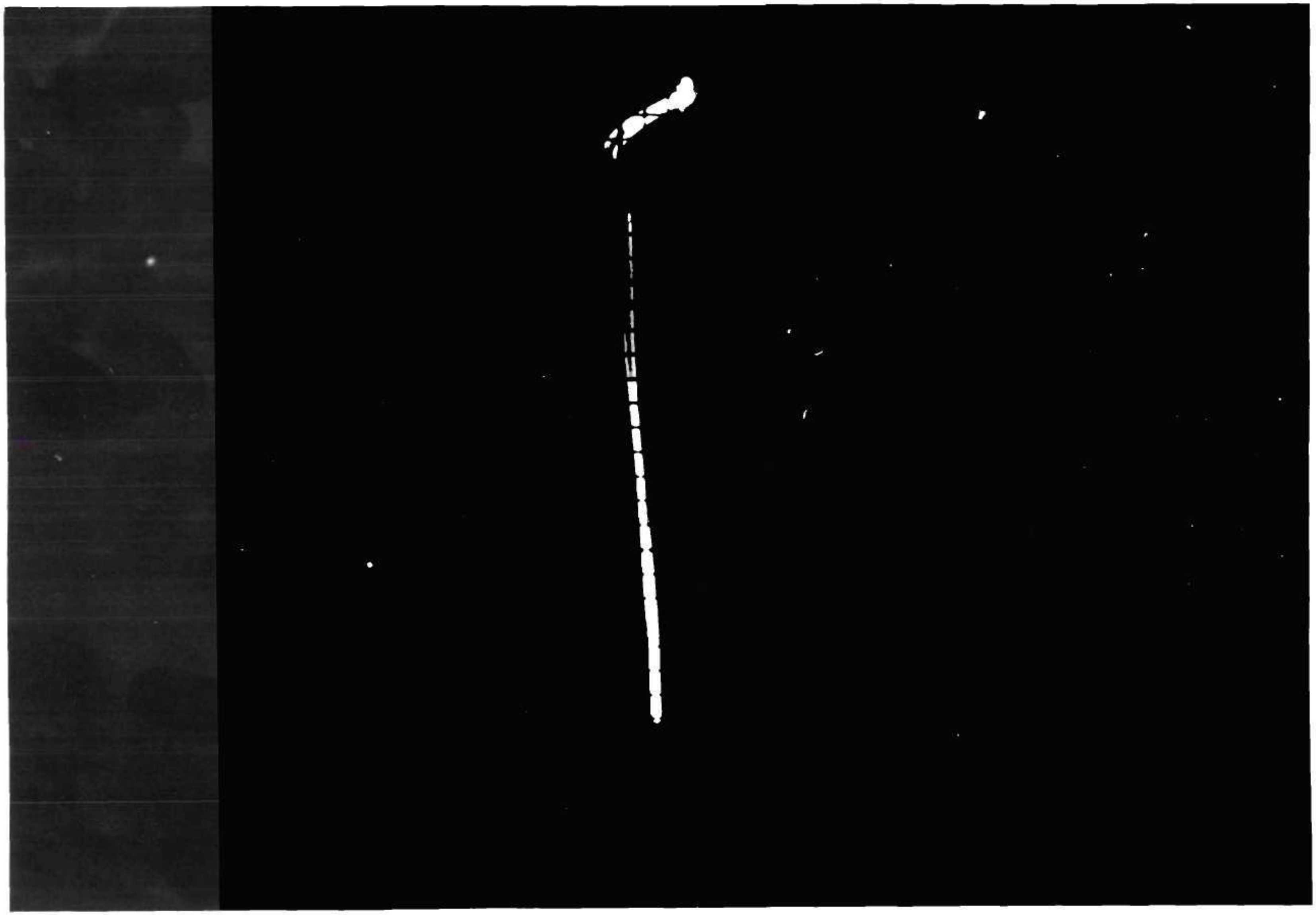

FIG.10 PARTIAL BREAKDOWN OF 1N34 CHARACTERISTIC WITH TEMPERATURE RISE

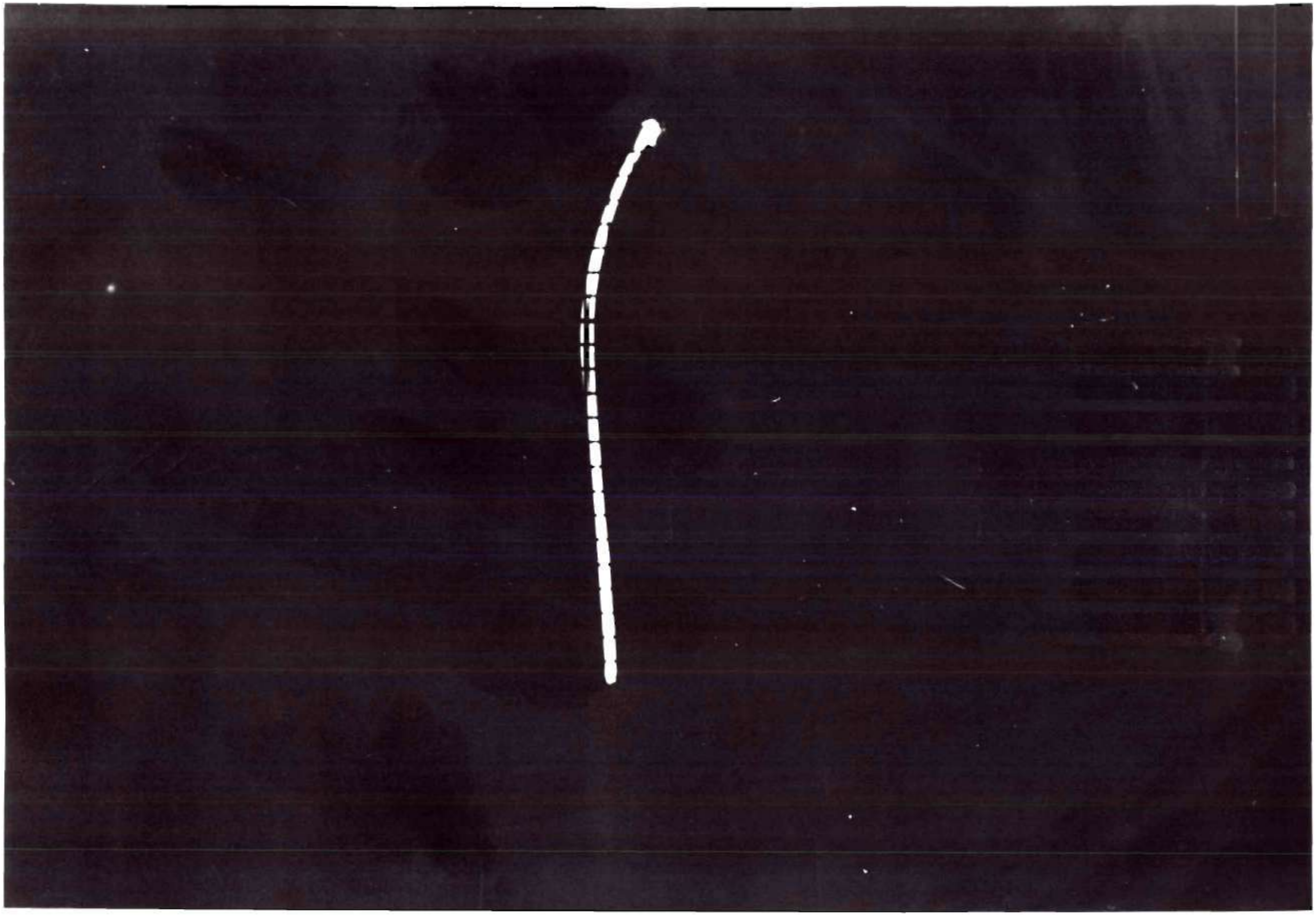

FIG. 11 COMPLETE BREAKDOWN OF 1N34 CHARACTERISTIC WITH TEMPERATURE RISE

ance. The effects of such temperature changes are minimized in the special mounting employed. The temperature of the crystal can remain nearer the ambient temperature because of the large radiating area provided. Exact specifications for the 1N34 and other commercial units of both germanium and silicon can be found in the literature.[6,7] A detailed discussion of types of contact points is also available.[8]

Dynamic Equivalent Circuit of the Diode

The dynamic equivalent circuit derives from the fact that energy from the negative resistance of the crystal diode can be supplied to a load. Therefore, the diode can be thought of as a generator having a negative resistance and an internal resistance, R_s, in series. The value of C_o is assumed negligible for purposes of simplification since it has a comparatively high reactance. The resultant characteristic of the equivalent generator is the negative slope of the characteristic curve.

Since the slope of this curve determines the characteristic of the generator, it is important to determine it accurately. This can be done in two ways; namely, by obtaining voltage and current meter readings and plotting a curve, or by obtaining the same information dynamically from a cathode-ray oscilloscope. The latter technique is more desirable. An ideal high negative resistance curve with a comparative scale is shown in Figure 12. Figure 13 shown two widely different characteristics which

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[6]E. C. Cornelius, loc. cit.

[7]W. E. Stephens, "Crystal Rectifiers," Electronics, Vol. 19, No. 7, pp. 112-119, July, 1946.

[8]A. W. Lawson, M. N. Lewis, P. H. Miller, and W. E. Stephens, op. cit.

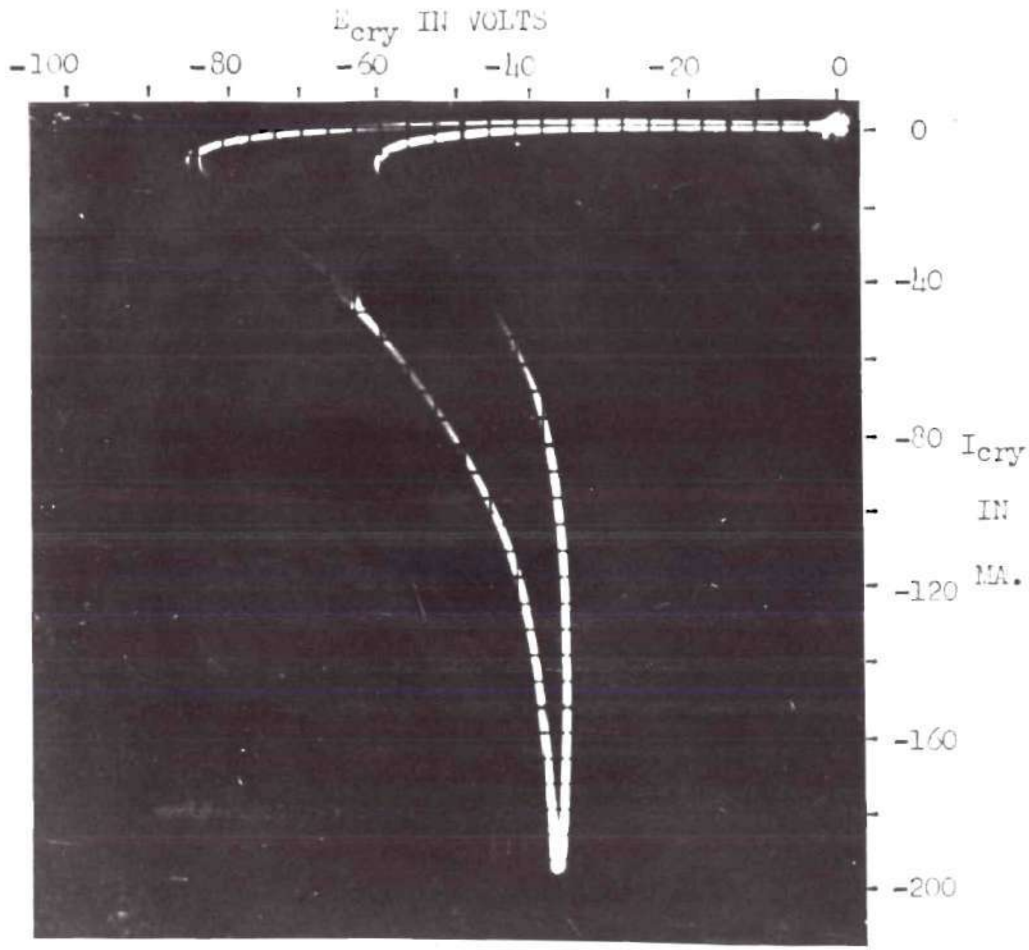

FIG. 12 IDEAL HIGH NEGATIVE RESISTANCE CHARACTERISTIC

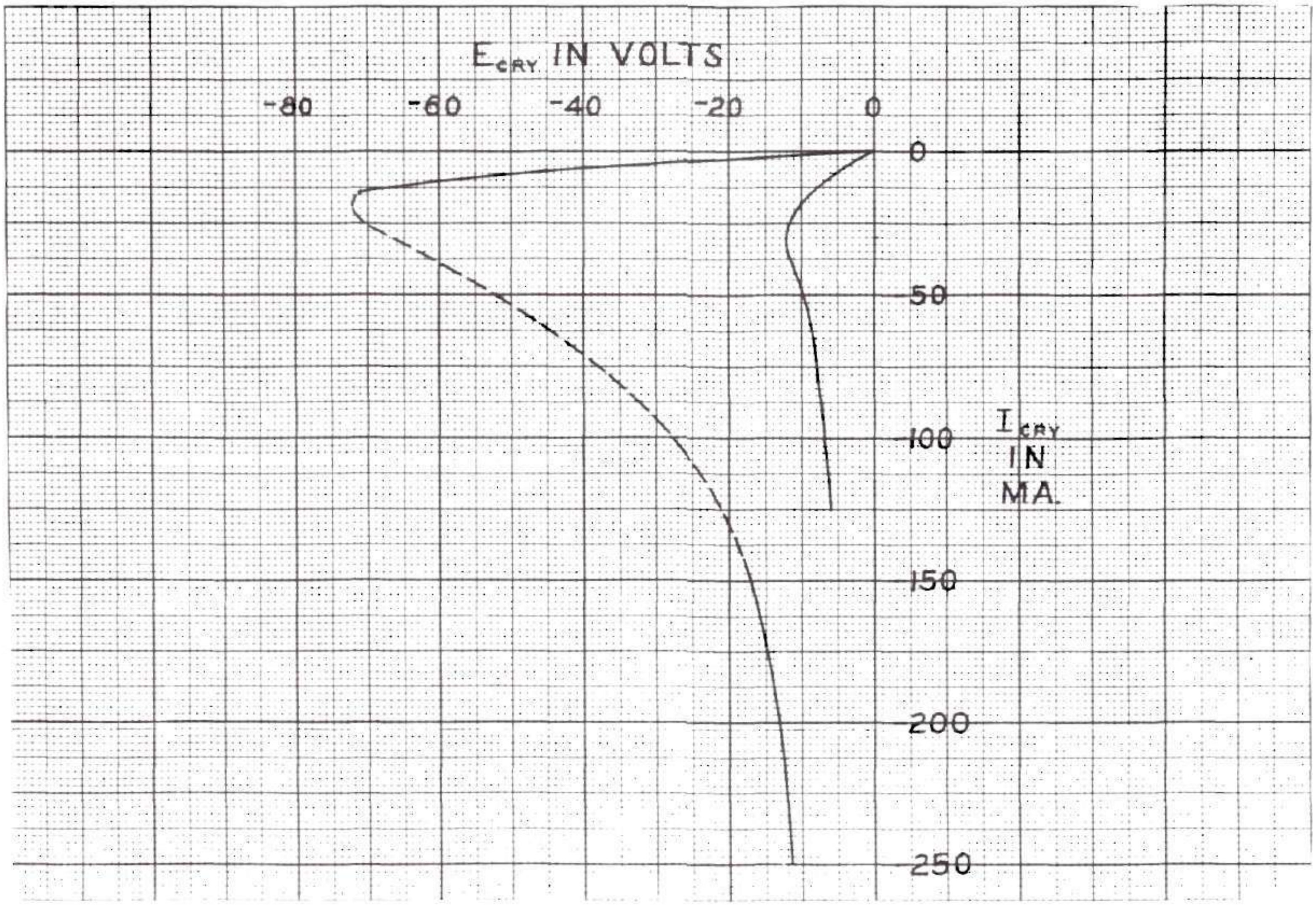

FIG. 13 COMPARISON OF TWO CHARACTERISTICS FROM DIFFERENT CRYSTALS

were obtained by plotting a number of points. The steep curve in Figure 13 has an unstable region where no points could be obtained. This section of the curve is shown with a dashed line.

Method for Obtaining Characteristic Curves

The dynamic pictures on the oscilloscope were obtained by applying the negative half-cycle of a 60-cycle voltage to the crystal. A resistance of about 500 ohms was placed in series with the crystal to obtain a voltage proportional to the current for vertical deflection. Figure 14 shows the actual voltage across the crystal and the current wave is shown in Figure 15. During the period of greatest current flow, the voltage wave is quite distorted. An explanation for this is given in the next section. The apparatus used is pictured in Figure 16 and the schematic connection in Figure 17.

When both the negative and the positive regions of the characteristic were desired, the rectifier was removed and the complete 60-cycle wave applied to the crystal. However, the use of the complete characteristic to predict crystal performance may not show the true picture. This is due to the extreme heating which occurs during the positive half-cycle, changing the crystal temperature. An advantage of using the single negative half-cycle then, is that the diode has a cooling period equal to a half-cycle per cycle of applied voltage.

When a point-by-point plot is made of a characteristic, it is difficult to duplicate the results for the same crystal. This is probably due to changing temperature conditions. Furthermore, it is to be noted that the oscilloscope trace is different on the increasing and decreasing

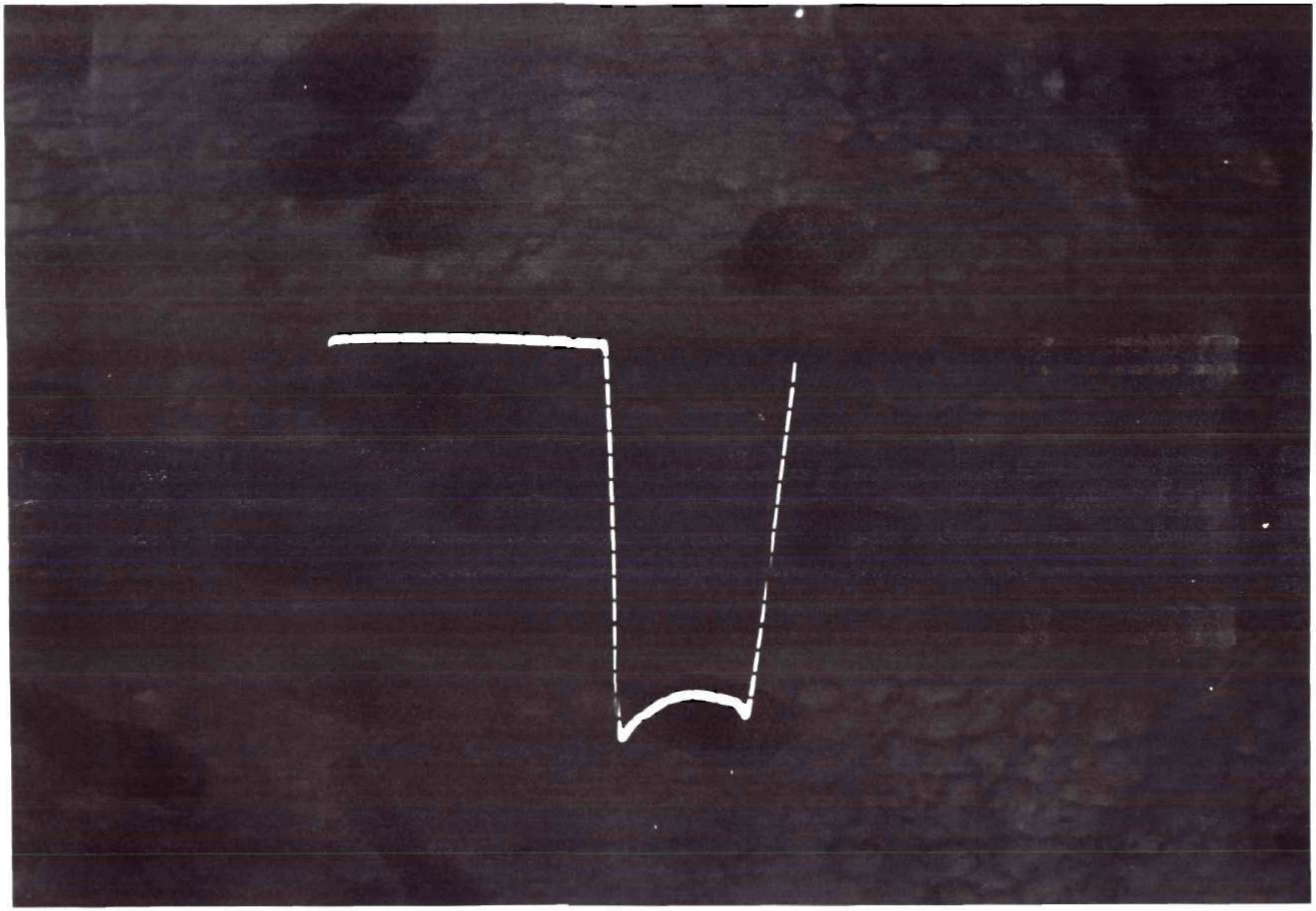

FIG. 14 VOLTAGE WAVEFORM ACROSS CRYSTAL WHILE DETERMINING CHARACTERISTIC

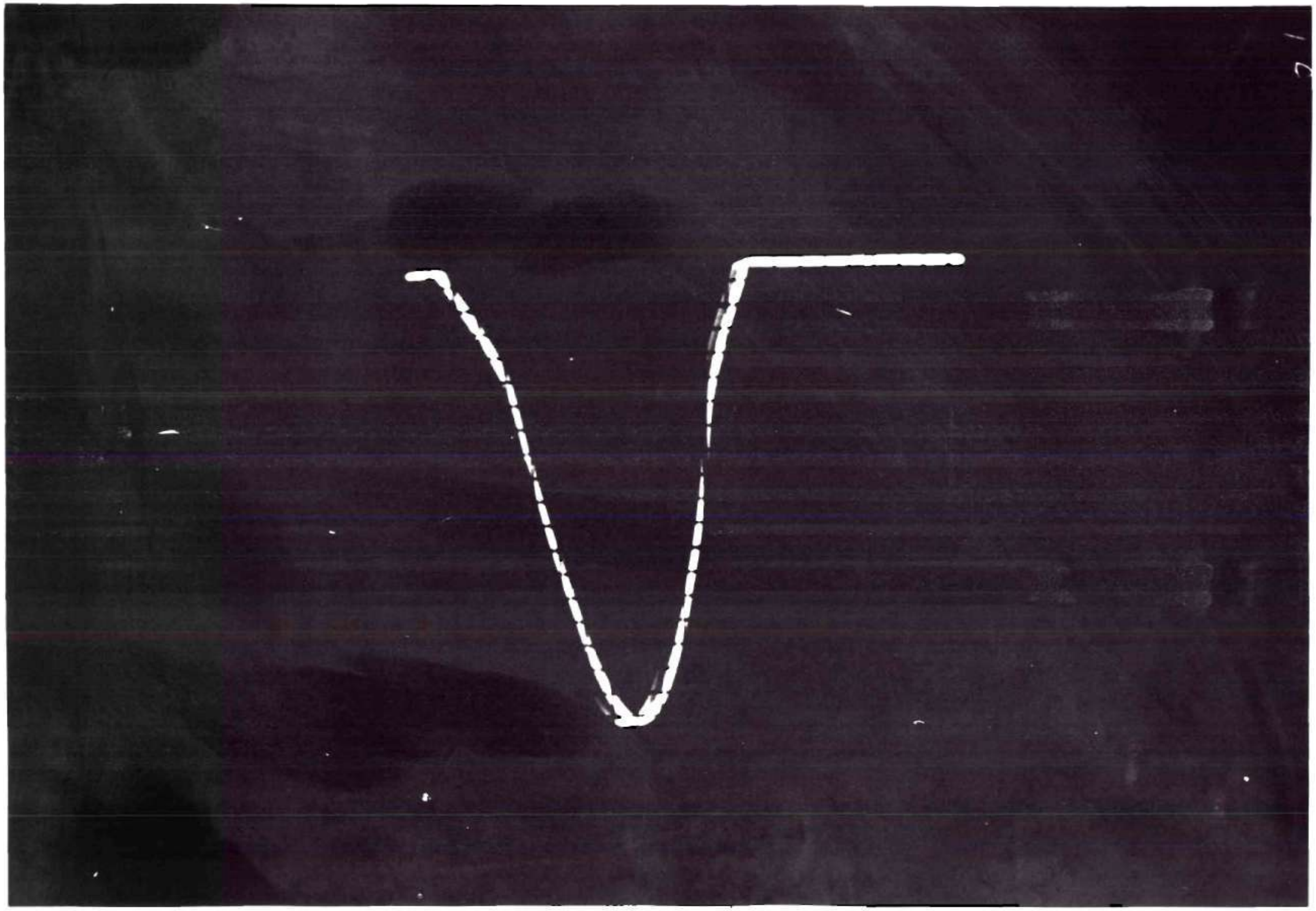

FIG. 15 CURRENT WAVEFORM ACROSS CRYSTAL WHILE DETERMINING CHARACTERISTIC

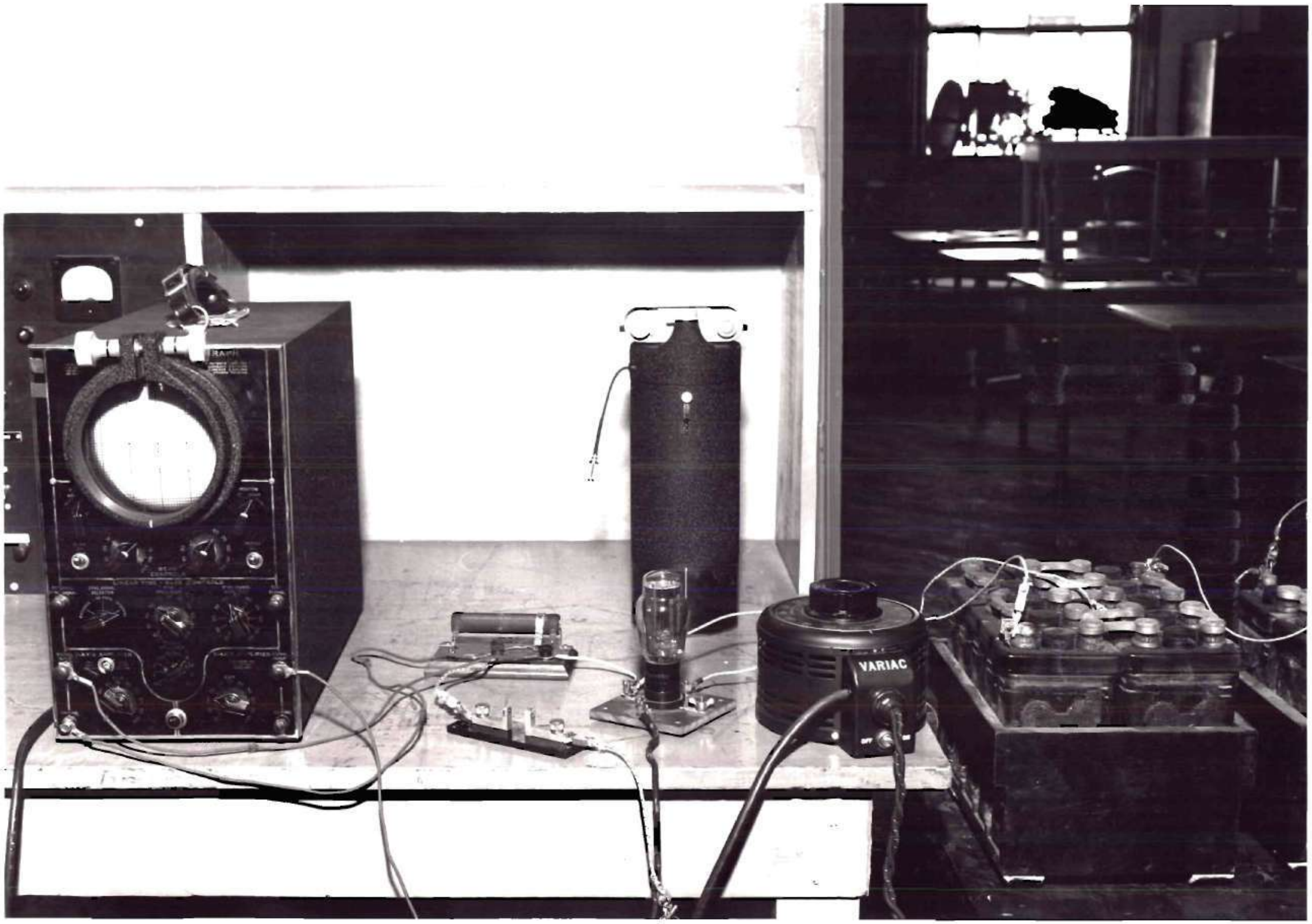

FIG. 16 EQUIPMENT FOR DYNAMIC MEASUREMENT OF CRYSTAL DIODE CHARACTERISTICS

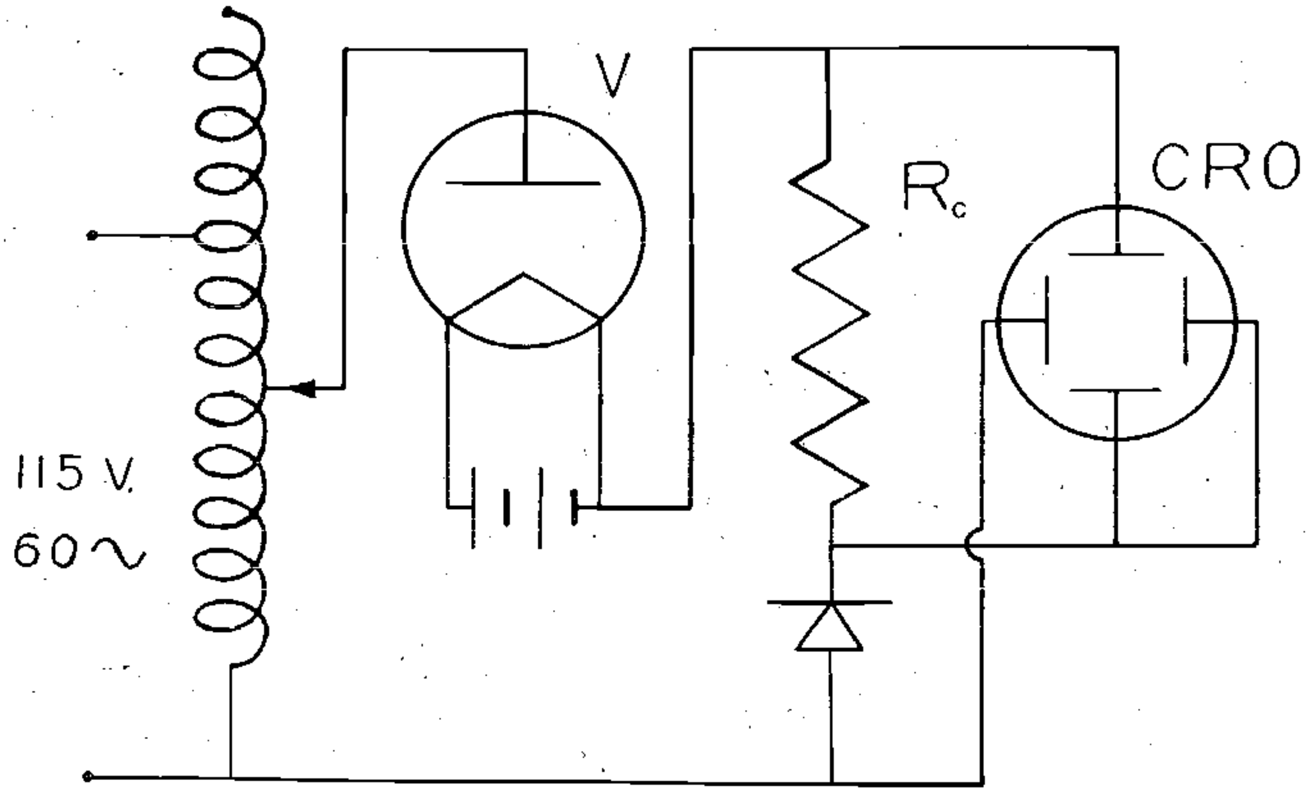

FIG. 17 CIRCUIT FOR OBTAINING DYNAMIC CHARACTERISTIC

halves of the negative half-cycle. This hysteresis loop may be due to transit-time effects appearing in the circuit.[9]

Operation Point for Negative Resistance

In order for the operation voltage of the diode to be adjustable, either a potentiometer or a rheostat must be used with the battery supply. The potentiometer arrangement is shown in Figure 18(a), and the rheostat arrangement in Figure 19(a). The battery voltage and either the potentiometer or the rheostat resistance can be chosen to facilitate adjustment to a desirable operating point. The unstable region may at the same time be reduced. A graphical solution of the problem is shown in Figure 18(b) for the potentiometer and in Figure 19(b) for the rheostat. For simplicity, the characteristics are shown with increasing voltage magnitude as positive.

In Figure 18(b), as R_1 is increased, the current follows the characteristic curve from 0 to A. At point A, a small increase in current causes a larger voltage drop across R_1, which reduces E. This action further increases the crystal current until an equilibrium point is finally reached at B. From that point further increases in current, as controlled by R_1, follow the characteristic curve. When the current is next decreased, it again follows the characteristic curve until point C is reached. At that point, the circuit conditions reverse their previous action until equilibrium is reached at D. The current then follows the characteristic to zero if the voltage is further reduced. The circuit of Figure 19(b)

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[9] E. W. Herold, op. cit., pp. 1206-7.

operates in a like manner. The only difference is the form of the equation for the straight lines. A detailed explanation of the above actions is described in the literature.[10]

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[10]H. J. Reich, "Trigger Circuits," Electronics, Vol. 12, No. 8, pp. 14-17, August, 1939.

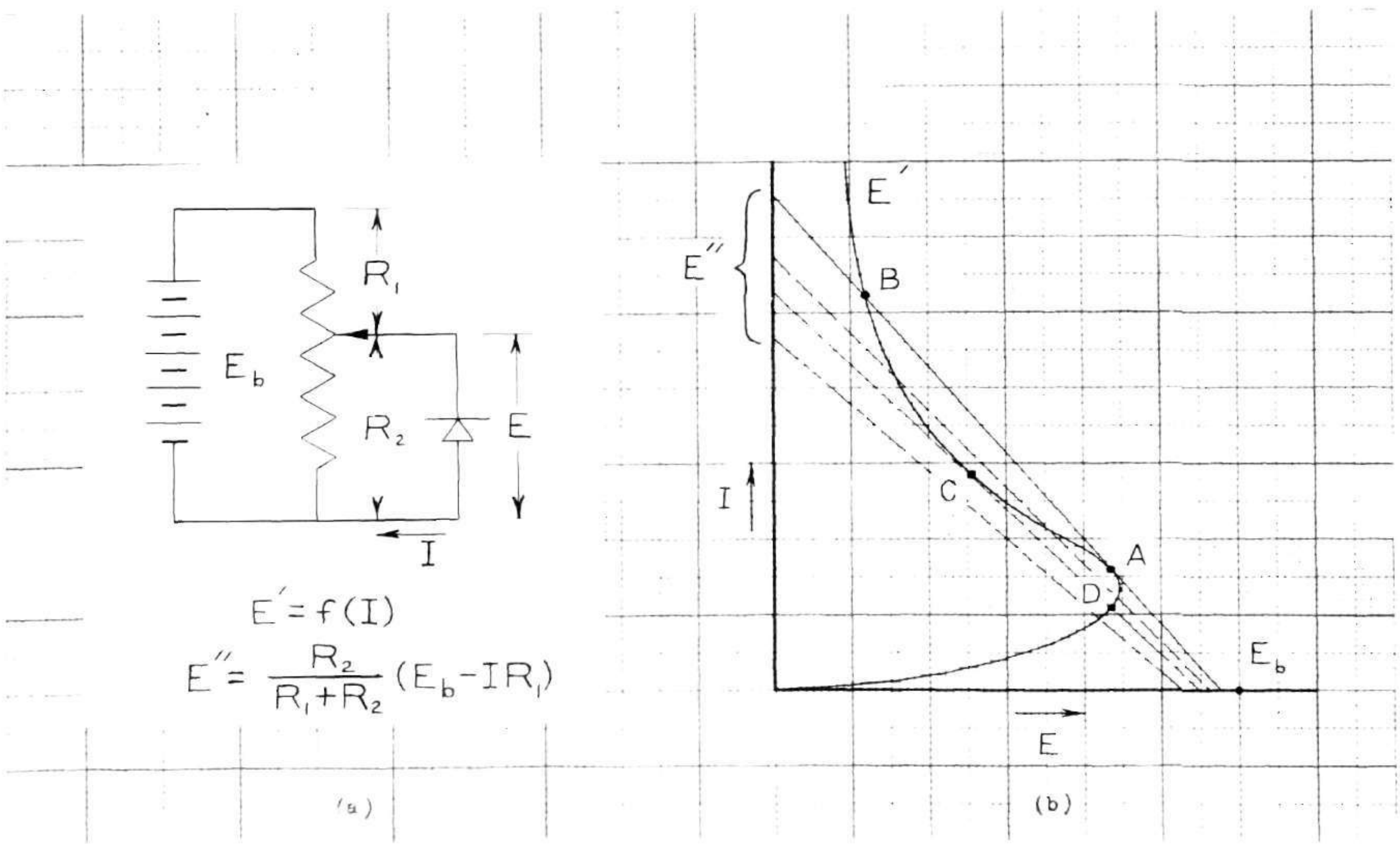

FIG. 18 POTENTIOMETER ARRANGEMENT FOR OBTAINING STATIC CHARACTERISTIC

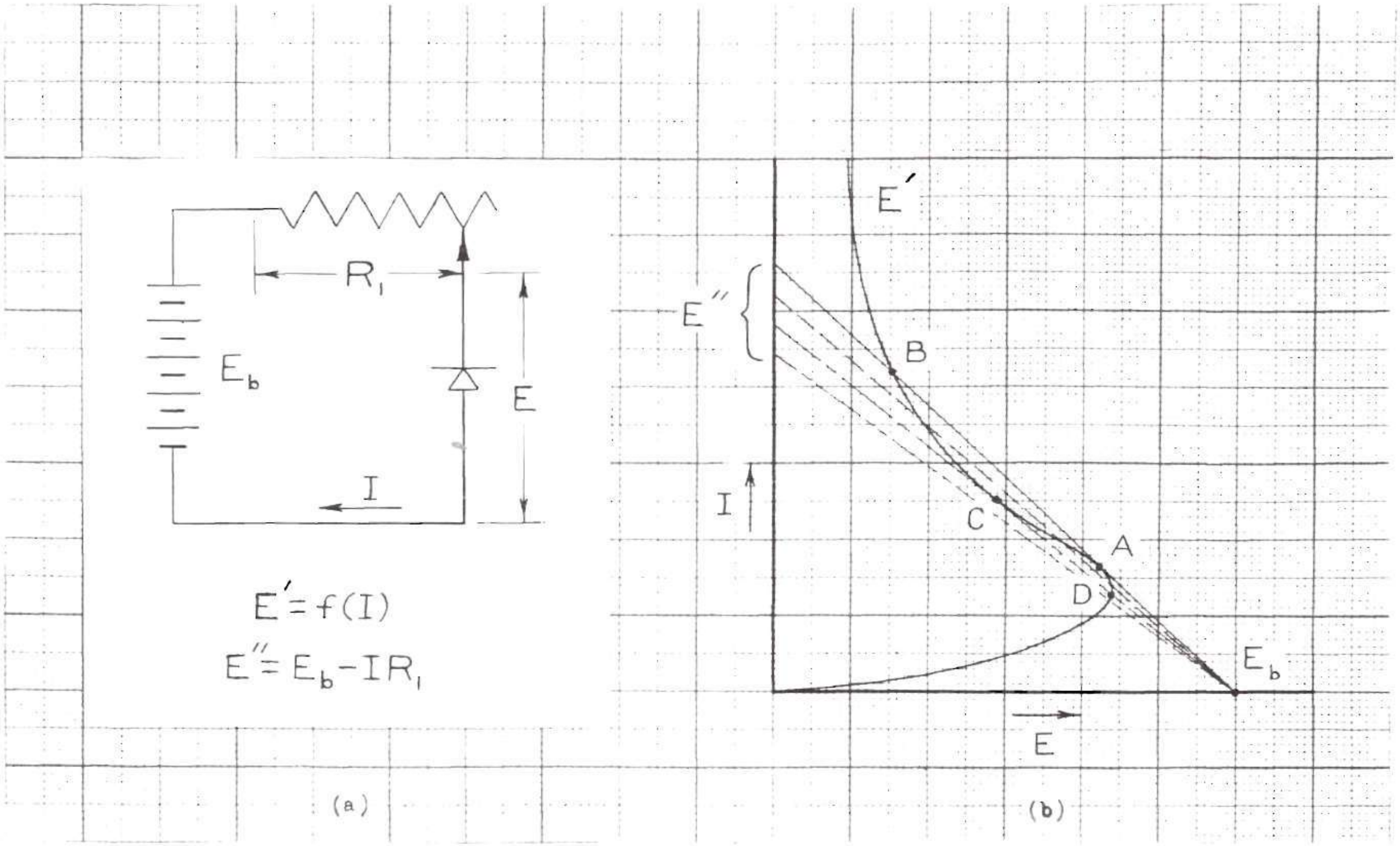

FIG. 19 RHEOSTAT ARRANGEMENT FOR OBTAINING STATIC CHARACTERISTIC

CRYSTAL DIODE OSCILLATORS

Sine-Wave Oscillator

The negative resistance properties of the crystal diode have been discussed with generally one idea, that of obtaining a high negative resistance characteristic. This type of characteristic is desirable for use in oscillatory circuits. Other types of characteristics may be desirable for other uses. For example, the low negative resistance may be used for voltage regulation.[11]

A circuit for a sine-wive oscillator is shown in Figure 20(a). The resonant circuit is series connected, since a parallel resonant circuit cannot be used without a large drain on the battery, which would result from the d-c path through the inductance. Also, a low impedance circuit should be used with current-controlled negative resistance devices.[12] Some typical circuit components and the measured frequency are given in Table I.

The negative resistance of the diode, when it is in the oscillator circuit, is taken directly from the negative slope of the characteristic. The amount of negative resistance placed in parallel with the resonant circuit, however, does not depend on the crystal diode alone. The effect of the potentiometer in parallel must be taken into account. From the mathematical consideration of two resistances in parallel, the equivalent resistance of the potentiometer must be numerically larger than the negative resistance of the diode in order for the resultant resistance

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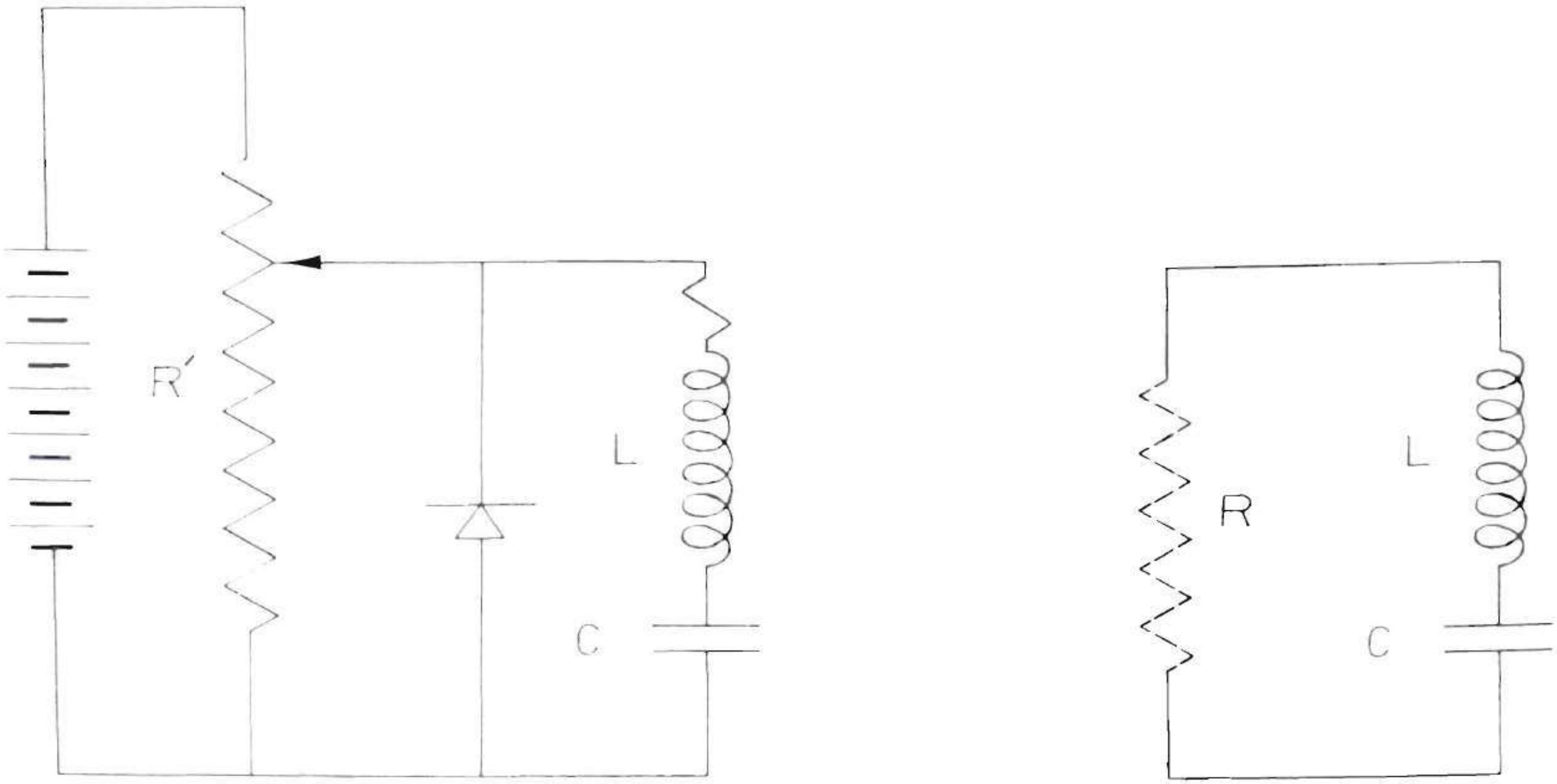
[11] E. C. Cornelius, op. cit., p. 122.

[12] E. W. Herold, loc. cit.



(a) (b)

FIG. 20 SINE-WAVE OSCILLATOR

to have a negative value. This inherently increases the effective negative resistance.[13] For the same reason, if a rheostat were in series with the battery, it should have a value less than the negative resistance. It has been found more convenient to use the potentiometer arrangement of Figure 18(a). If the potentiometer resistance is made very large, however, it will have a negligible effect on the negative resistance developed.

A method of keeping the impedance of the source supply voltage high is to place a large inductive impedance in one of the leads from the potentiometer to the diode. Although this is equivalent to adding a small amount of inductance in series with the resonant circuit, it also keeps the total negative resistance near that of the diode alone. At a given frequency a large L to C ratio in the resonant circuit will help to minimize the effect of the blocking inductance on the resonant frequency. Typical component values are given in Table II.

Another variation of the series resonant circuit of Figure 20(a) is obtained by connecting the leads from the potentiometer across the crystal diode and inductance in series. This places the full d-c voltage from the potentiometer across the condenser. The circuit still oscillates near the same frequency as before but a mathematical analysis would be more difficult than for the previous circuit. No particular advantage can be gained with this arrangement.

Analysis of the Sine-Wave Oscillator

In order to simplify the representation of the quantities involved, the total resistance of the circuit will be designated by R. This equiva-

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[13] Ibid., pp. 1206-9.

lent resistance includes the potentiometer or rheostat resistance, the coil resistance, and the diode resistance. This value can be either positive or negative. Since the coil has a high Q, its resistance is low. This will make the total resistance essentially equal to the potentiometer or rheostat resistance, and diode resistance in parallel. The dynamic equivalent circuit for Figure 20(b) then has the resistance, R, the inductance, L, and the capacitance, C, in series.

The voltage drops around the dynamic equivalent circuit above are

$$L\frac{di}{dt} + Ri + \frac{1}{C}\int i\,dt = 0 \qquad (1)$$

Differentiating once and dividing by L gives

$$\frac{d^2i}{dt^2} + \frac{R}{L}\frac{di}{dt} + \frac{1}{LC}i = 0 \qquad (2)$$

This is an ordinary linear differential equation which has as its solution

$$i = \epsilon^{-at}\left[k \sin\sqrt{b^2 - a^2}\,t + k' \cos\sqrt{b^2 - a^2}\,t\right] \qquad (3)$$

where

$$a = \frac{R}{2L}$$

$$b = \frac{1}{\sqrt{LC}}$$

The constants k and k' are arbitrary. To evaluate them, time is chosen as zero when the circuit is just ready to break into oscillation. The current is then zero, and there can be no abrupt change of current with the inductance in the circuit. Applying these conditions to equation (3) shows that k' is zero. The form of the final equation for the current is then

$$i = k\epsilon^{-at} \sin \sqrt{b^2 - a^2}\,t \qquad (4)$$

The constant, k, is determined from some known set of conditions other than when the current is zero. It will vary for different crystals.

The variation in magnitude of the resistance, R, will cause two different types of oscillation, depending on whether it is negative or zero. When it is negative, the oscillation will expand until changing conditions make the resistance positive. At that point the oscillations will cease and the circuit will return to its original status only to start the cycle again. In order for R to become positive, the amplitude of oscillation must reach an inflection point in the negative resistance characteristic,[14] or else the losses incurred, as the frequency increases during the cycle, must become greater than the negative resistance. From equation (4), it is evident that the frequency can increase during the cycle as R changes. Furthermore, the negative resistance portion of R is directly related to the amplitude of oscillation.[15] An example of the type of wave produced is shown in Figure 21. At high natural resonant frequencies the dielectric and skin effect losses limit the operation to a small portion of the characteristic. This makes the operation more

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[14]Herbert J. Reich, Theory and Applications of Electron Tubes, First Edition, McGraw-Hill Book Company, Inc., 1939, p. 315 and pp. 354-5.

[15]C. Brunetti, "The Clarification of Average Negative Resistance with Extensions of Its Use," Proceedings of the Institute of Radio Engineers, Vol. 25, No. 12, pp. 1604-15, December, 1937.

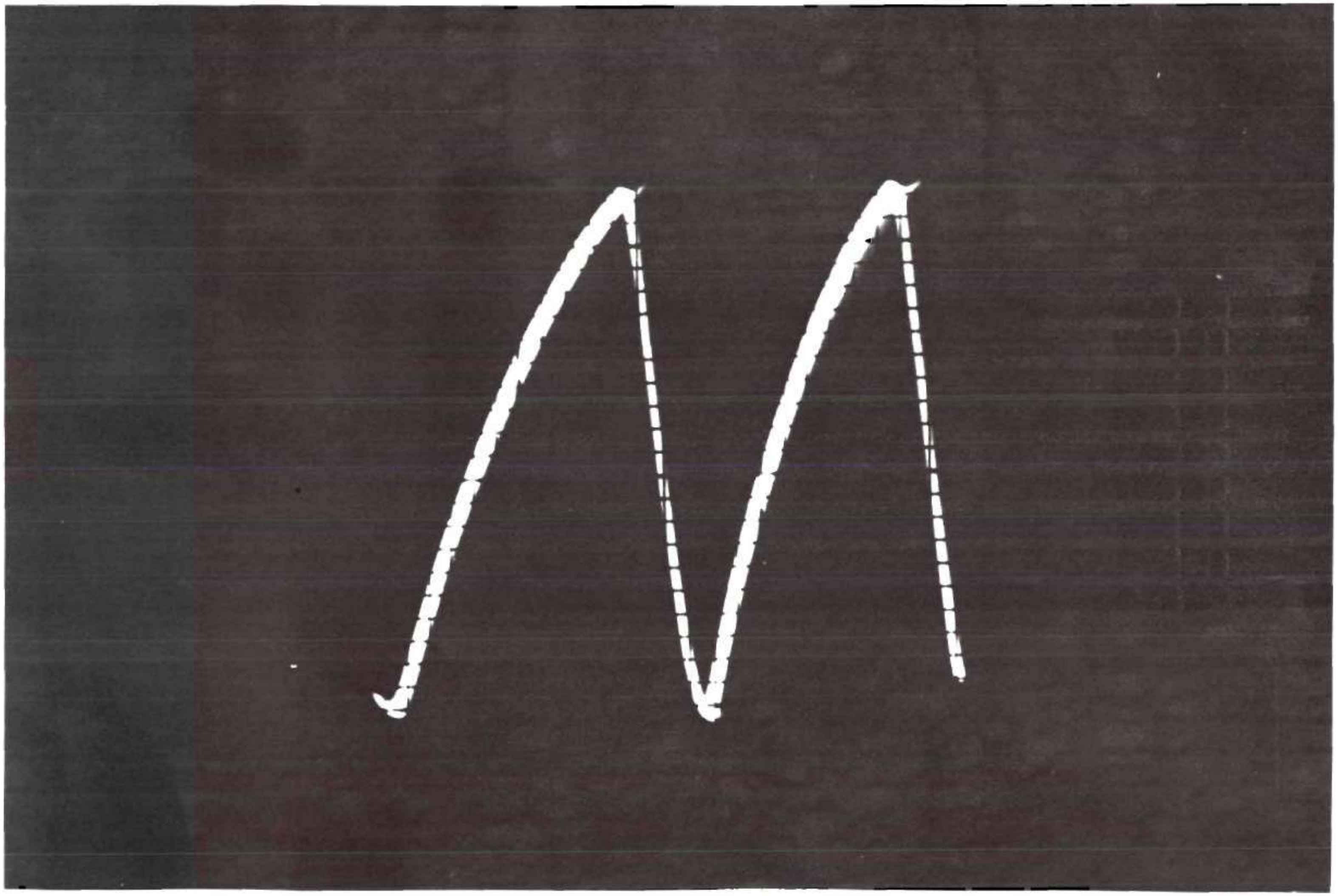

FIG. 21 VOLTAGE ACROSS CONDENSER AT LOW AUDIO FREQUENCY

nearly linear and results in wave shapes more nearly sinusoidal.

A special case of equation (4) occurs when the total resistance approaches zero. The current then approaches

$$i = k \sin bt \tag{5}$$

This equation is independent of the resistance and shows that under the condition imposed the oscillator can produce pure sine waves at any frequency.

Discussion

The voltage wave across each element of the oscillator circuit was observed and recorded for various frequency ranges up to about 74 kilocycles for the circuit of Figure 20(a). Improvement toward a pure sine wave was noticed in each of the voltages as the frequency increased. The condenser voltage is shown in the audio frequency range in Figures 21, 24, and 25. A definite change is noticeable.

The voltage across the inductance has very sharp peaks and is zero for a large part of the cycle at low frequencies. Greatest change in its form occurs in the audio frequency range as illustrated in Figures 22, 26, and 27. At 70 kilocycles, the voltage is very nearly a sine wave as shown in Figure 28.

The best sine-wave shape was observed across the crystal. The difference in shape between a frequency of 400 cycles as shown in Figure 23, and 32 kilocycles as shown in Figure 29, was the greatest improvement noted. The same improvements in wave shape could be obtained by adjusting the resistance to approach the boundary condition, R equal zero.

The vertical gain of the oscilloscope was not necessarily the same

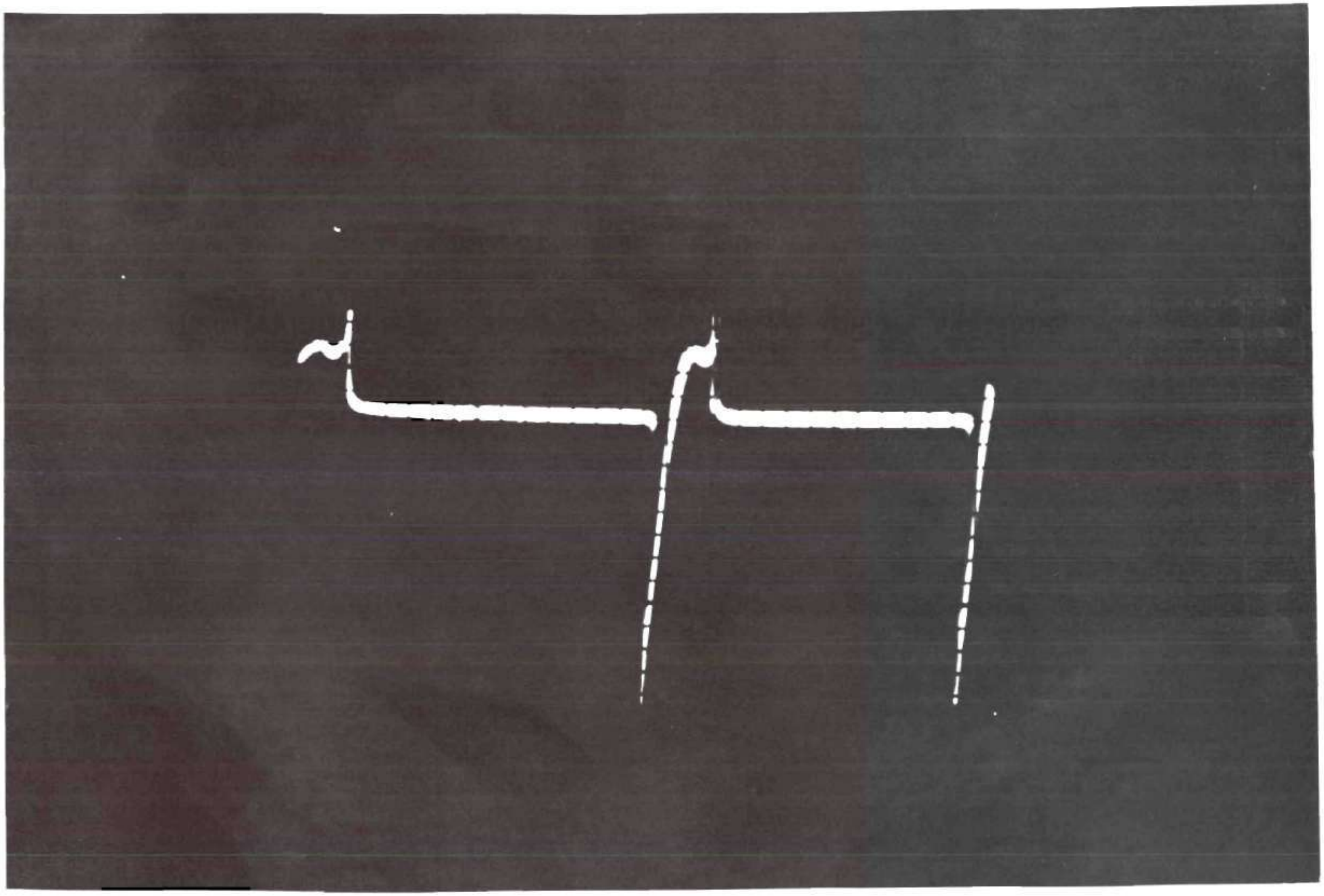

FIG. 22 VOLTAGE ACROSS INDUCTANCE AT LOW AUDIO FREQUENCY

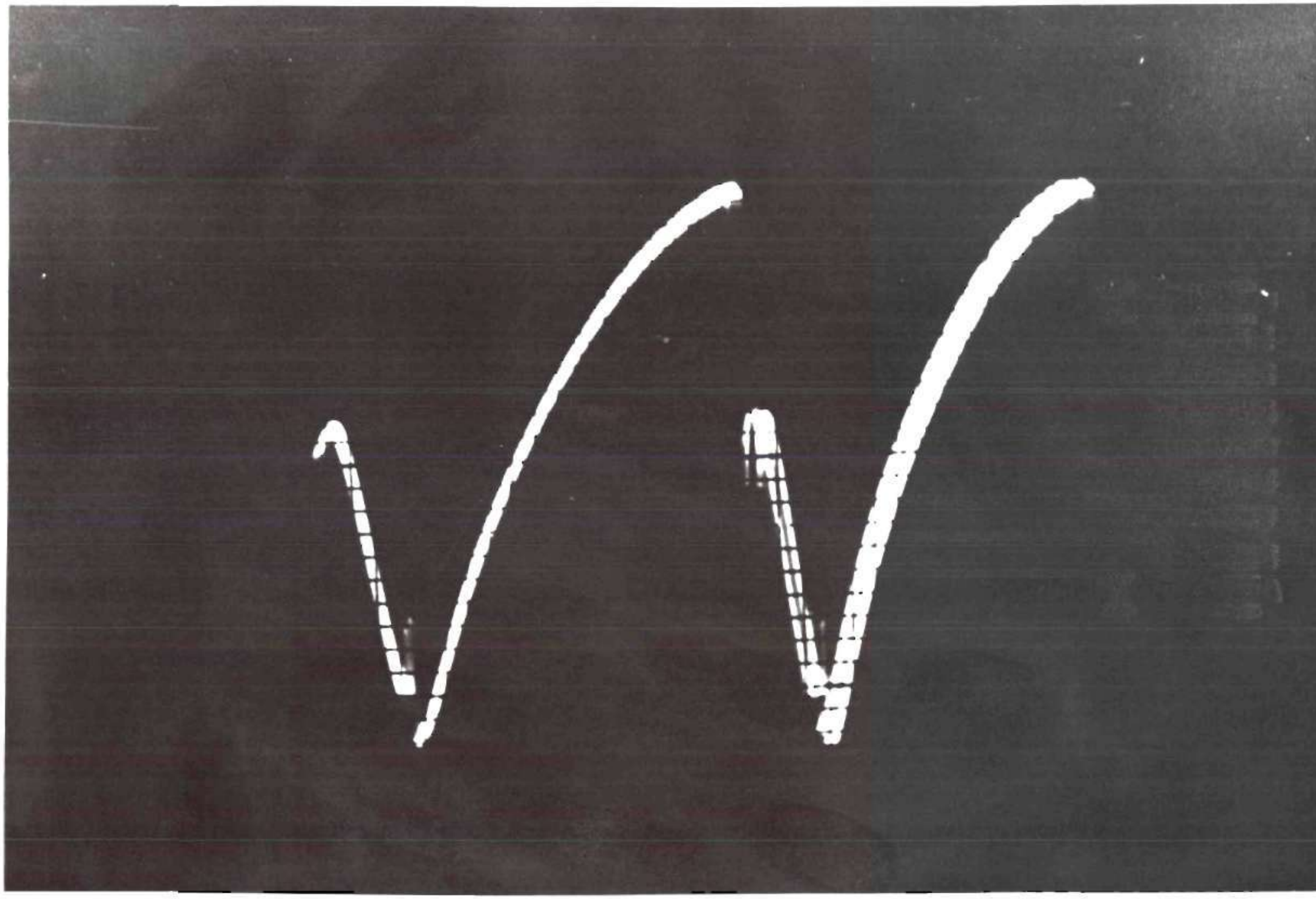

FIG. 23 VOLTAGE ACROSS CRYSTAL AT LOW AUDIO FREQUENCY

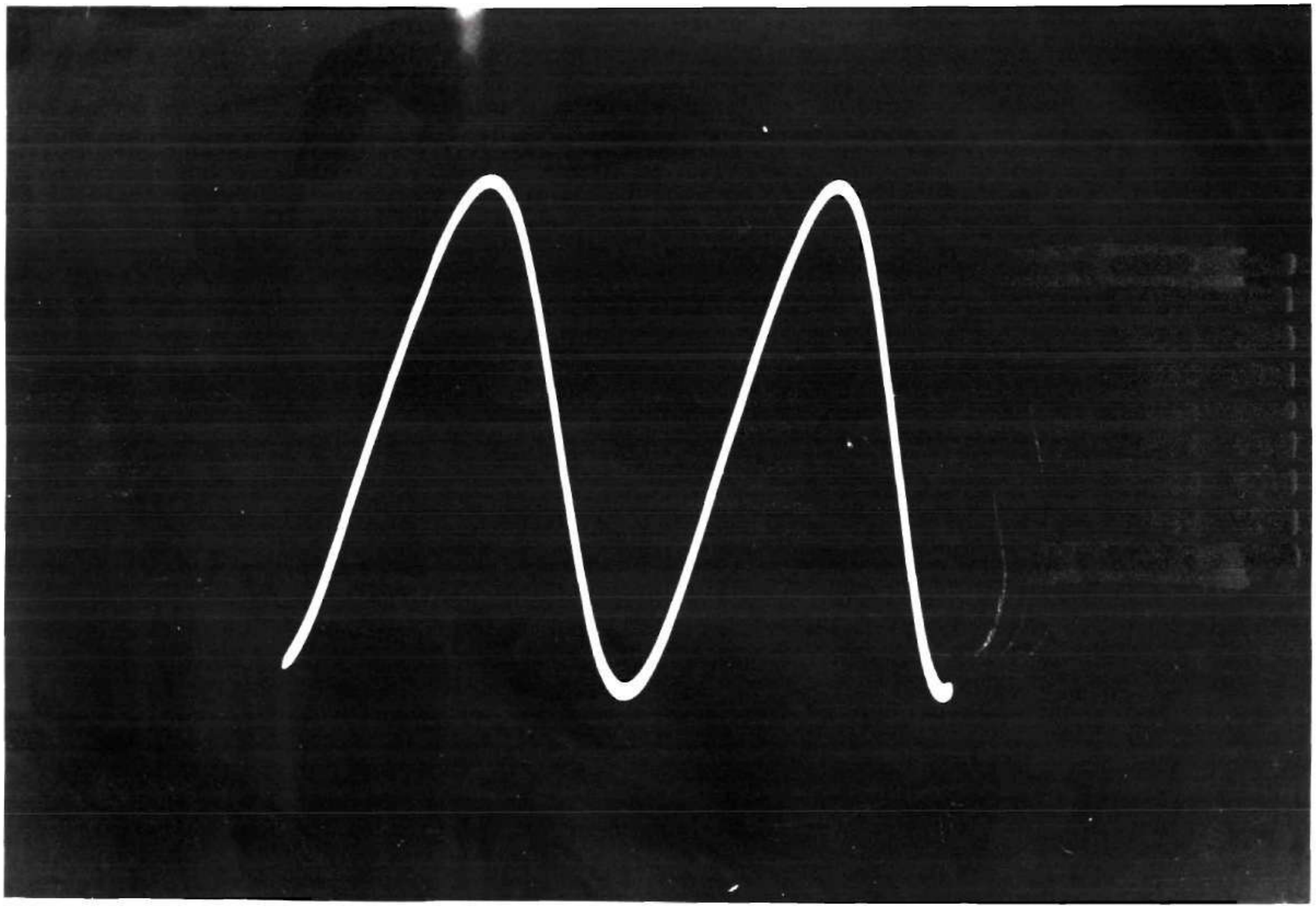

FIG. 24 VOLTAGE ACROSS CONDENSER AT MIDDLE-RANGE AUDIO FREQUENCY

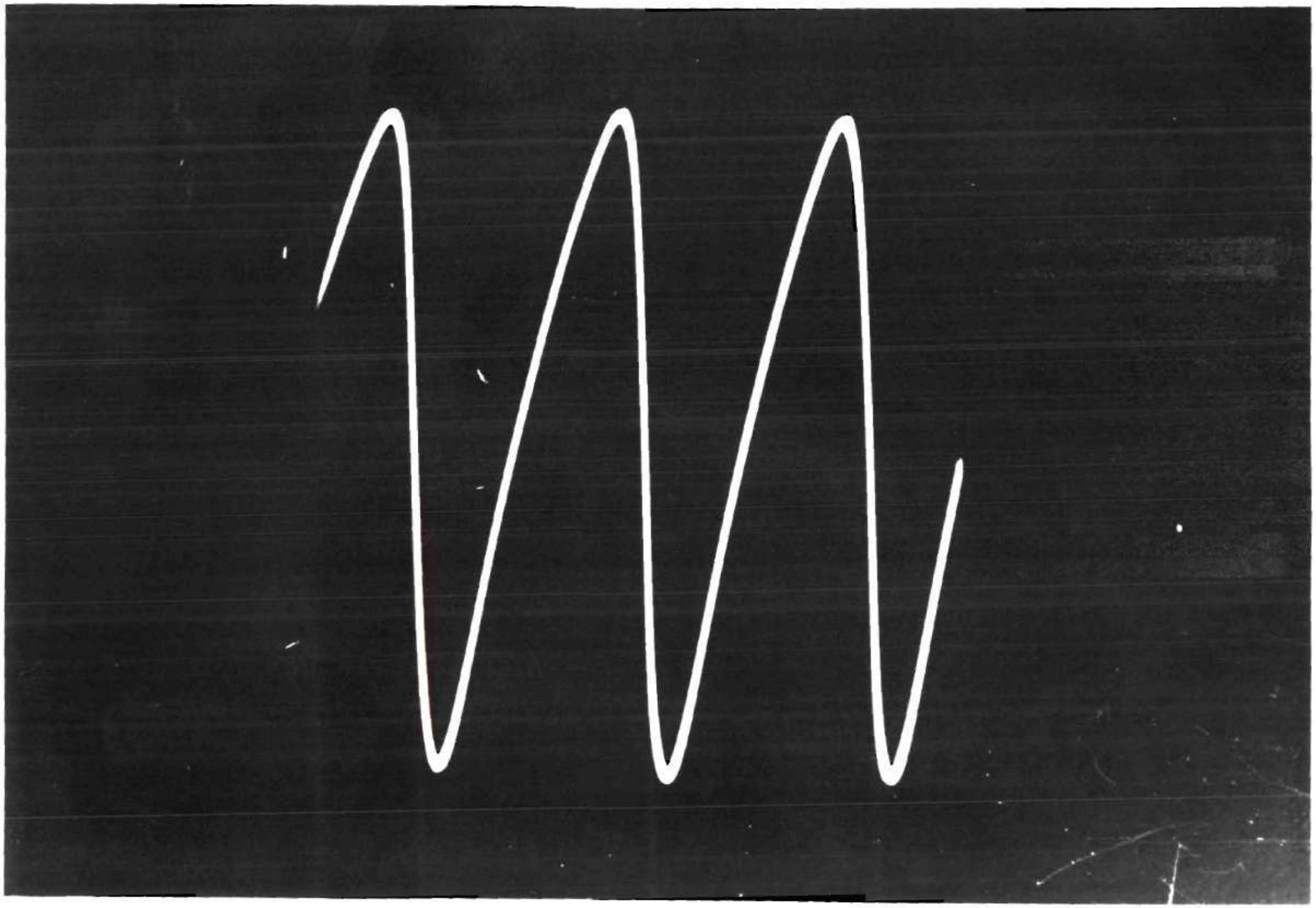

FIG. 25 VOLTAGE ACROSS CONDENSER AT HIGH AUDIO FREQUENCY

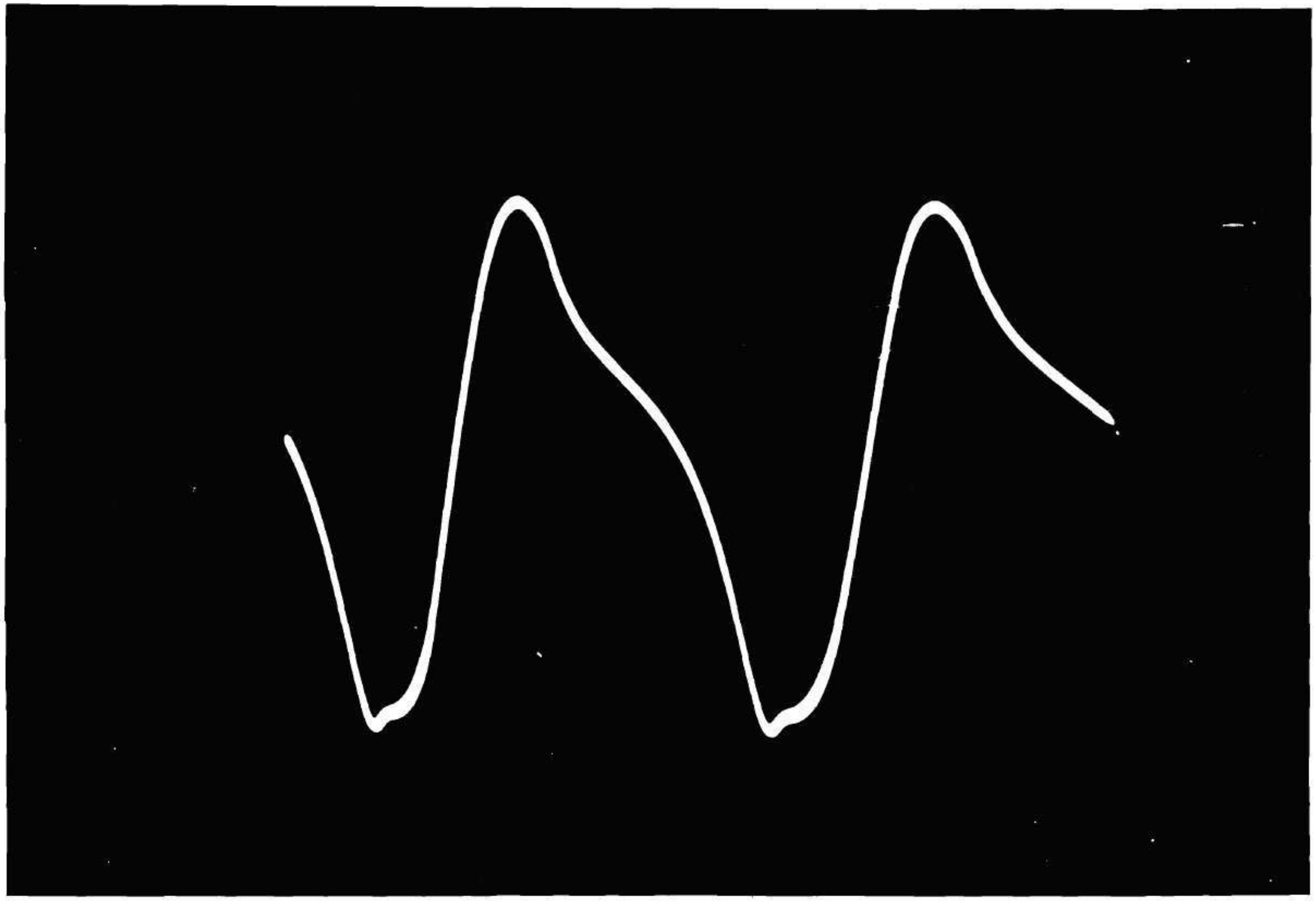

FIG. 26 VOLTAGE ACROSS INDUCTANCE AT HIGH AUDIO FREQUENCY

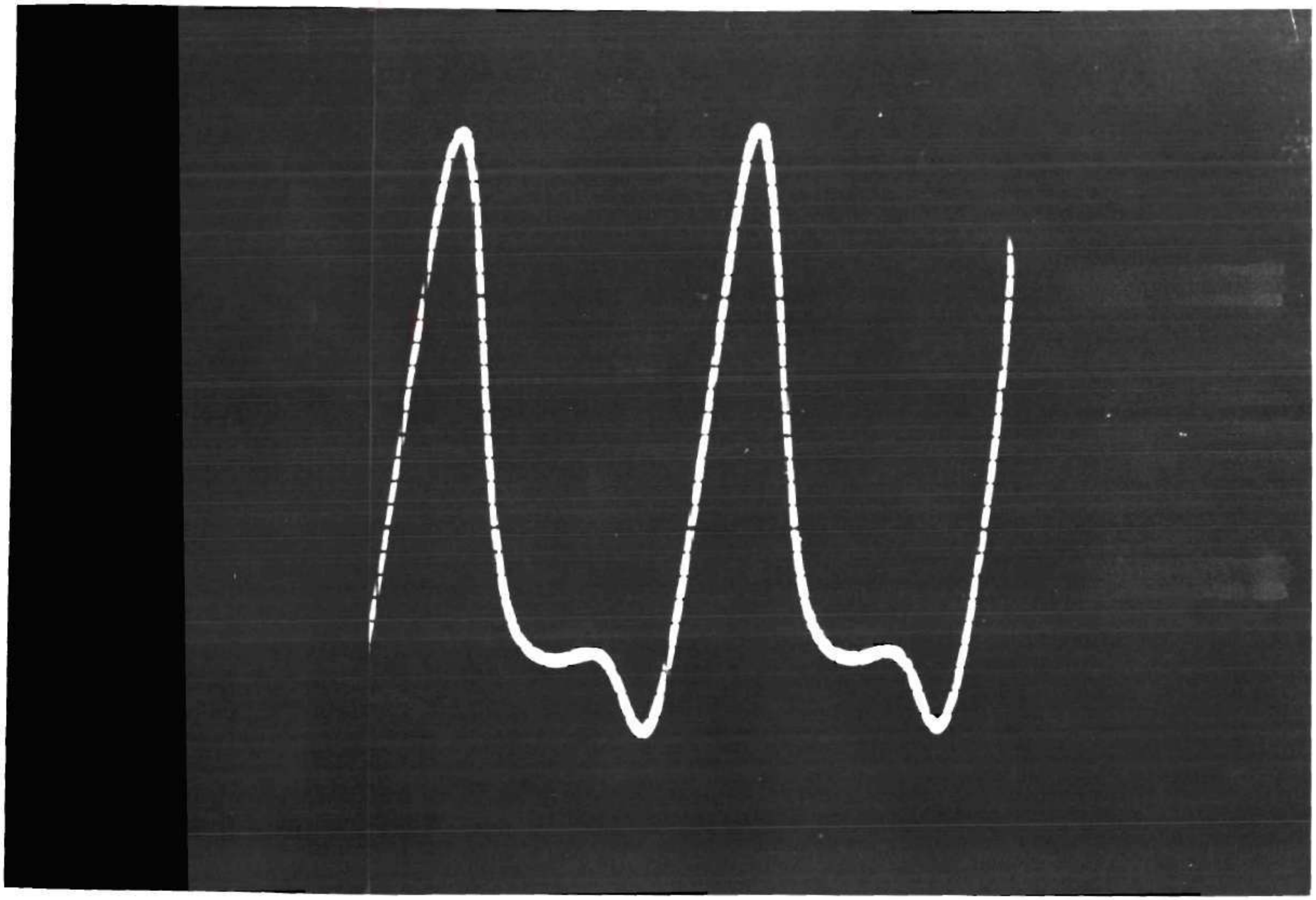

FIG. 27 VOLTAGE ACROSS INDUCTANCE ABOVE AUDIO FREQUENCIES

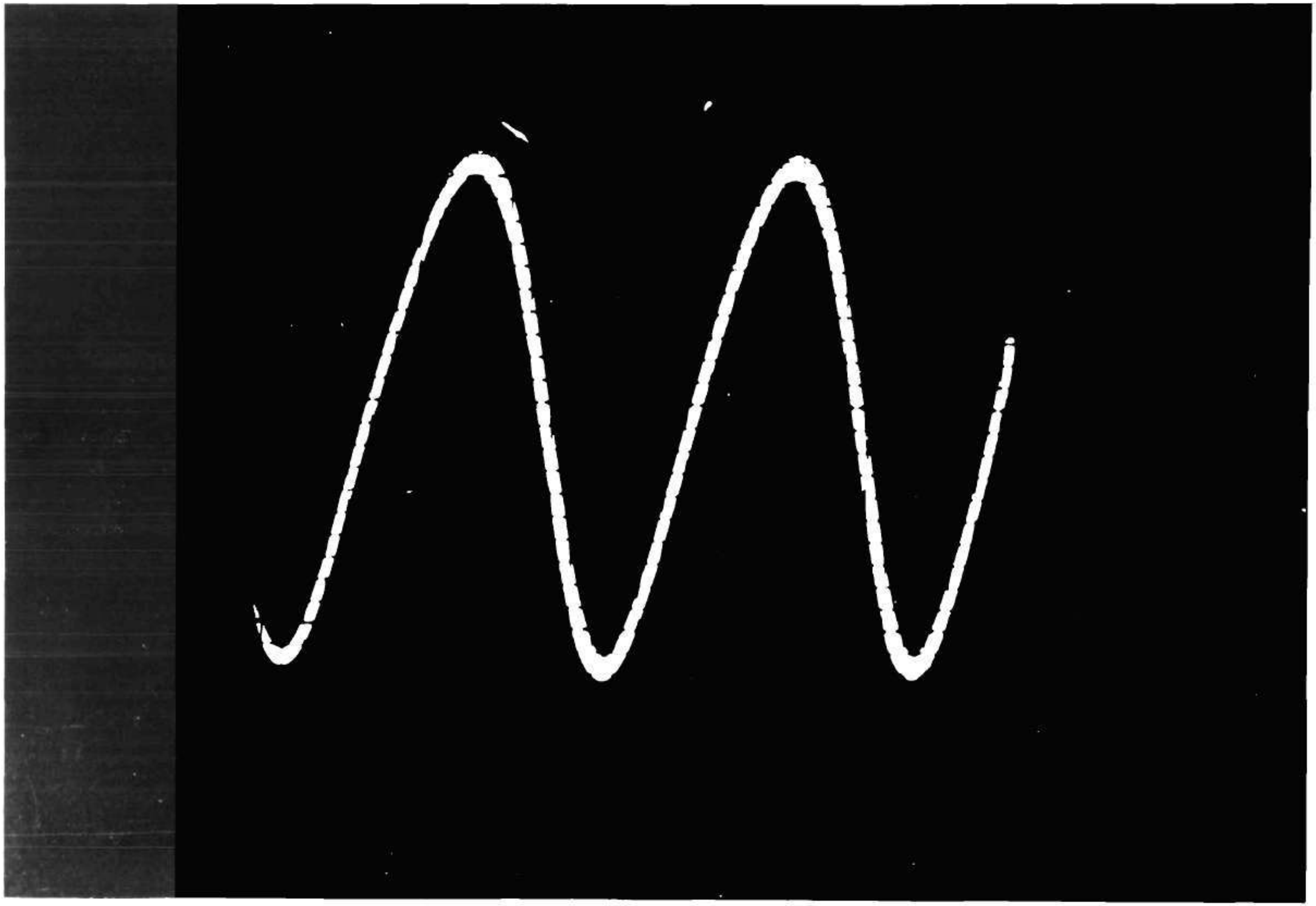

FIG. 28 VOLTAGE ACROSS INDUCTANCE AT 70 KILOCYCLES

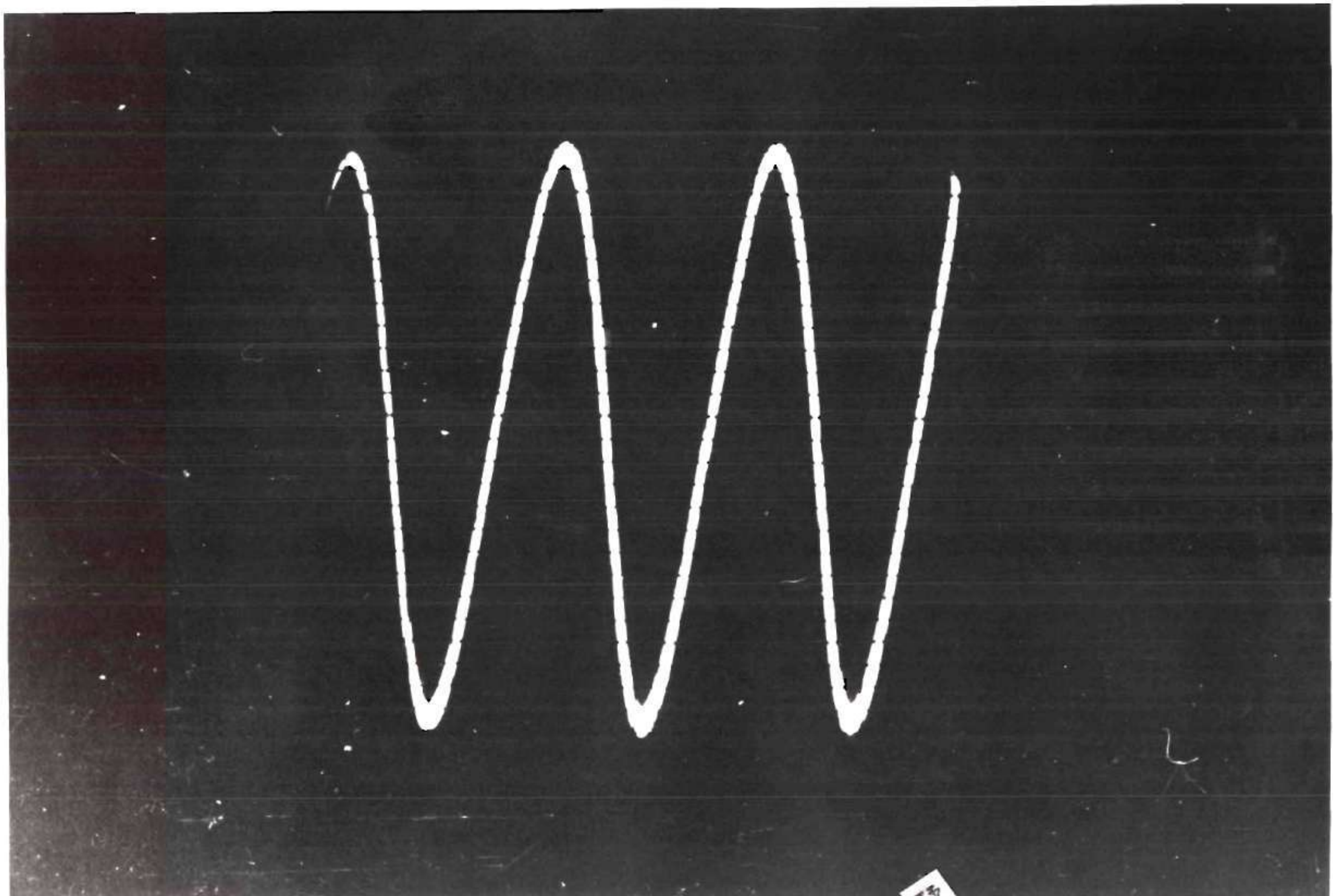

FIG. 29 VOLTAGE ACROSS CRYSTAL ABOVE AUDIO FREQUENCIES

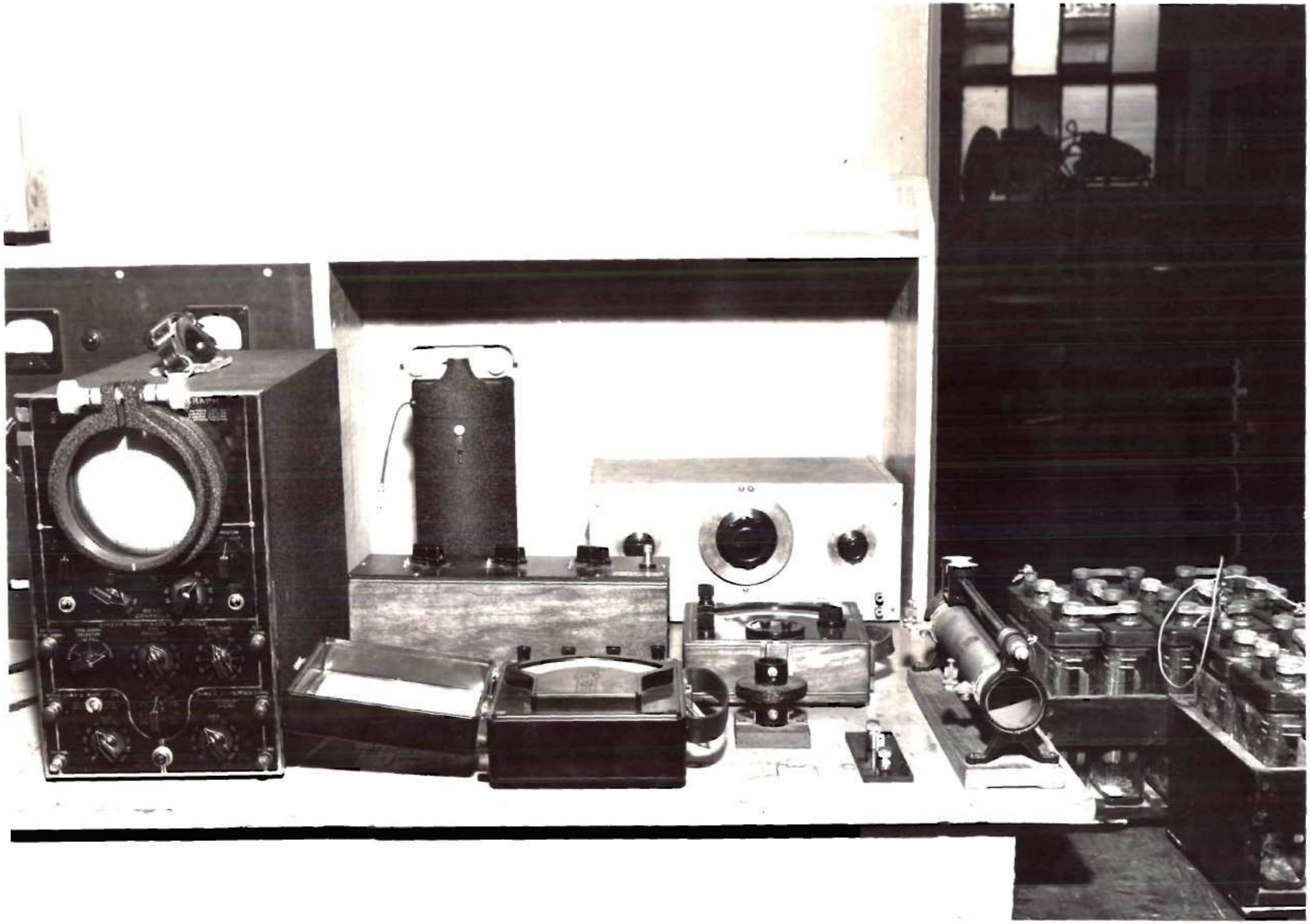

FIG. 30 EQUIPMENT FOR SINE-WAVE OSCILLATOR AND FREQUENCY MEASUREMENT

in all of the above Figures. The maxima of Figures 21, 22, and 23, however, do relate the three observed voltages at a frequency of 400 cycles.

The highest frequency attained was 500 kilocycles. This is less than the upper frequency limit of one megacycle suggested in the literature.[16] Perhaps with other circuit arrangements illustrated in the literature a higher frequency could have been attained.[17]

Relaxation Oscillator

If the inductance of the sine-wave oscillator is made vanishingly small, then oscillations in a relaxation mode take place.[18] The circuit of this oscillator is shown in Figure 31. The frequency is now a function of the time constant of the circuit.

A possible explanation of the action in this oscillator is as follows: Assume that the circuit is oscillating and that the steady state condition has been reached. At the instant the condenser has zero charge the operating point for the diode is in the negative resistance region. A large current begins to flow into the condenser almost instantaneously from the negative resistance. As the rate of flow decreases, however, the operating point of the diode moves toward a lower current and higher voltage. When the inflection point is reached the total resistance is zero and the condenser discharges. The large discharge current moves the operating point to the position originally assumed, and the cycle repeats itself.

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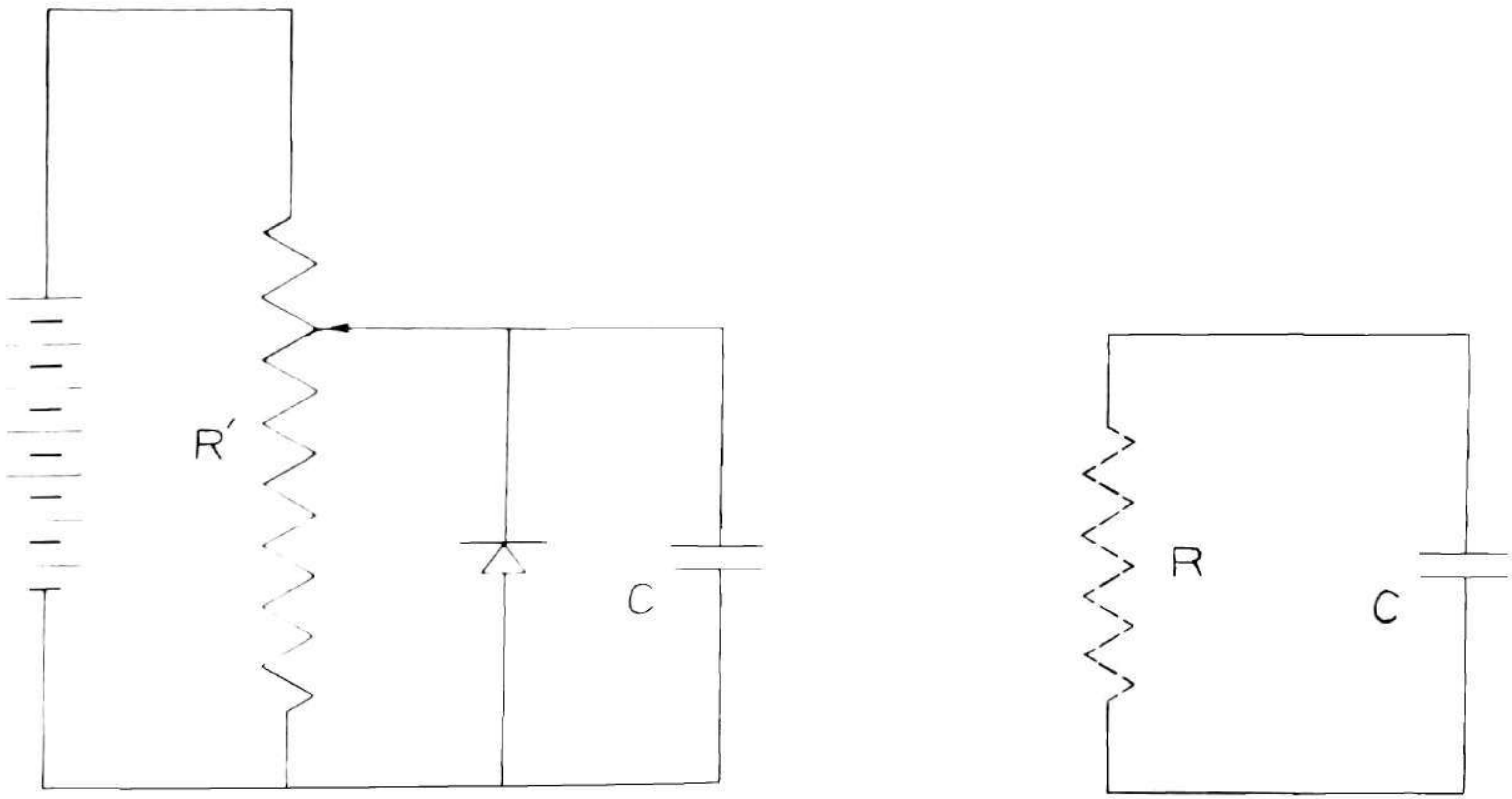
[16] E. C. Cornelius, *loc. cit.*

[17] *Ibid.*

[18] E. W. Herold, *loc. cit.*



(a) (b)

FIG. 31 RELAXATION OSCILLATOR

The analysis of some types of resistance-capacitance oscillators shows that they can be used for a sine-wave output.[19,20] The circuit above does not lend itself to this type of application, however. Some tendency toward a sinusoidal output was noted when an inductive type of potentiometer was used. The upper frequency limit of 500 kilocycles suggested in the literature was not reached.[21]

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[19] Paul S. Delaup, "Sinewaves in R-C Oscillators," Electronics, Vol. 14, No. 1, pp. 34-36, January, 1941.

[20] C. Brunetti, "A Practical Negative Resistance Oscillator," Review of Scientific Instruments, Vol. 10, pp. 85-88, March, 1939.

[21] E. C. Cornelius, loc. cit.

CONCLUSIONS

The germanium crystal diode has an equivalent circuit composed primarily of resistance and a small amount of capacitance shunted across the larger part of that resistance. The capacitance is usually negligible for frequencies less than 1500 megacycles. The resistance, however, is voltage dependent and varies in such a manner as to exhibit a negative a-c resistance in the characteristic curve.

The characteristics of different diodes are not uniform in either amplitude or shape. They do, however, conform to one general pattern. In the inverse direction, this is a peak followed by the negative slope. The variations in the shape of the curves are affected greatly by temperature changes in the crystal.

Characteristic curves can be determined either statically or dynamically. The dynamic trace shows evidence of a hysteresis curve, which may be explained by the combined effects of temperature, transit time, and the analysis presented in connection with Figure 18. Portions of the characteristic which appear unstable in either method of obtaining the curves are due to the choice of circuit parameters.

The investigation conducted on oscillators shows that the sine-wave oscillator can be stable up to 100 kilocycles, and that frequencies as high as 500 kilocycles are obtainable. These crystal oscillators are capable of generating a wave having excellent frequency stability. Relaxation oscillations as well as sine waves were the primary voltages observed on the circuit components. At low audio frequencies, however, a sharp pulse was observed across the inductance. A small resistance placed in series with the diode yielded triangular pulses with a broad base.

Removal of the inductance in the series resonant oscillator converts it to a relaxation oscillator. The frequency is then dependent on the time constant of the circuit. A quasi-sinusoidal voltage was observed across the condenser for the higher frequencies. This was due to the residual inductance of the potentiometer.

It must be borne in mind that the crystal diodes used in this investigation were not designed for the rough usage which they received. A crystal diode designed around the conditions outlined herein should give much more satisfactory results in stability. In addition, the contact junction between the crystal and its holder was not considered in any of the effects noted.[22] This may bear investigation.

The use of many devices is cyclical in nature, with new applications bringing them forth again and again. The crystal diode is one of these devices. Even as this is written the crystal diode is being used experimentally for amplification. These uses may eventually be limited if continued investigations are not made into the characteristics of the basic element itself -- the crystal diode.

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[22] General Radio Experimenter, "Vacuum-Tube and Crystal Rectifiers as Galvanometers and Voltmeters at Ultra-High Frequencies," Vol. 19, No. 12, May, 1945.

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APPENDIX

TABLE I: Component Values and Frequency for Series Resonant Circuit of Figure 20(a).

E_b (volts)	80	80	80	80	80
R' (ohms)	6000	6000	6000	6000	6000
L (mh)	7.1	7.1	7.1	7.1	7.1
C (μf)	0.550	0.100	0.050	0.040	0.003
f_n (cps)	2550	5970	8450	9440	34500
f_m (cps)	2200	3000	5700	6000	33000

APPENDIX

TABLE II: Component Values and Frequency for Series Resonant Circuit with Highly Inductive Source.

E_b (volts)	80	80	80	80
R' (ohms)	6000	6000	6000	6000
L_s (mh)	510	510	510	510
L (mh)	7.1	7.1	7.1	7.1
C (μf)	0.003	0.001	0.000625	0.0005
f_n (cps)	30100	59750	75500	84500
f_m (cps)	32000	60000	70000	74000